Prepared in cooperation with the Missouri Department of Natural Resources

Peak Discharge, Flood Profile, Flood Inundation, and Debris Movement Accompanying the Failure of the Upper Reservoir at the Taum Sauk Pump Storage Facility near Lesterville, Missouri

Scientific Investigations Report 2006–5284

U.S. Department of the Interior
U.S. Geological Survey

Front Cover. Upper reservoir embankment failure at the Taum Sauk pump storage facility near Lesterville, Missouri, January, 2006 (photograph published with permission from MACTEC Engineering and Consulting, Inc.).

Back Cover. Flow over the spillway of the lower reservoir, on the recession of the embankment failure flood at the Taum Sauk pump storage facility near Lesterville, Missouri, December 14, 2005 (photograph by C. Shane Barks, U.S. Geological Survey).

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By Paul H. Rydlund, Jr.

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[In pocket]

Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mi (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mi (mi^2)	259.0	hectare (ha)
square mi (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-ft (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
ton per year (ton/yr)	0.9072	metric ton per year
	Pressure	
pound per square foot (lb/ft^2)	4.882	kilogram per square meter (k/m^2)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (k/m^3)
	Hydraulic gradient	
foot per mi (ft/mi)	0.1894	meter per kilometer (m/km)

Left and right pertain to an observer facing downstream.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Peak Discharge, Flood Profile, Flood Inundation, and Debris Movement Accompanying the Failure of the Upper Reservoir at the Taum Sauk Pump Storage Facility near Lesterville, Missouri

By Paul H. Rydlund, Jr.

Abstract

The Taum Sauk pump-storage hydroelectric power plant located in Reynolds County, Missouri, uses turbines that operate as pumps and hydraulic head generated by discharging water from an upper to a lower reservoir to produce electricity. A 55-acre upper reservoir with a 1.5- billion gallon capacity was built on top of Proffit Mountain, approximately 760 feet above the floodplain of the East Fork Black River. At approximately 5:16 am on December 14, 2005, a 680-foot wide section of the upper reservoir embankment failed suddenly, sending water rushing down the western side of Proffit Mountain and emptying into the floodplain of East Fork Black River. Flood waters from the upper reservoir flowed downstream through Johnson's Shut-Ins State Park and into the lower reservoir of the East Fork Black River. Floods such as this present unique challenges and opportunities to analyze and document peak-flow characteristics, flood profiles, inundation extents, and debris movement.

On December 16, 2005, Light Detection and Ranging (LiDAR) data were collected and used to support hydraulic analyses, forensic failure analyses, damage extent, and mitigation of future disasters. To evaluate the impact of sedimentation in the lower reservoir, a bathymetric survey conducted on December 22 and 23, 2005, was compared to a previous bathymetric survey conducted in April, 2005. Survey results indicated the maximum reservoir capacity difference of 147 acre-feet existed at a pool elevation of 730 feet.

Peak discharge estimates of 289,000 cubic feet per second along Proffit Mountain and 95,000 cubic feet per second along the East Fork Black River were determined through indirect measurement techniques. The magnitude of the embankment failure flood along the East Fork Black River was approximately 4 times greater than the 100-year flood frequency estimate of 21,900 cubic feet per second, and approximately 3 times greater than the 500-year flood frequency estimate of 30,500 cubic feet per second. Dynamic wave unsteady flow models Dam Break (DAMBRK) and Unsteady NETwork (UNET) were used to route the flood wave from the embankment failure breach of the upper reservoir to the spillway of the lower reservoir. Simulated velocities ranged from 20 to 51 feet per second along Proffit Mountain and 12 to 32 feet per second along the East Fork Black River. Simulated arrival time of the flood wave took approximately 5.5 to 6.0 minutes to enter into the floodplain of the East Fork Black River, and roughly 29 minutes to begin filling the lower reservoir. Simulated shear stress values reached as high as 232 pounds per square foot along the slope of Proffit Mountain and 144 pounds per square foot within the Shut-Ins. Flood depths from the embankment failure may have reached greater than 50 feet along Proffit Mountain and as much as 30 to 40 feet along the East Fork Black River.

A steady-state model was used to develop 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood frequency profiles along the East Fork Black River. A similar flood event, hypothetically resulting from a breach of the east embankment above Taum Sauk Creek, was simulated along with the 100- and 500-year flood profiles on Taum Sauk Creek. Estimated extents of flood inundation were developed for each profile.

Debris movement was extensive as a result of the flood wave moving down Proffit Mountain and through Johnson's Shut-Ins State Park. A quantitative assessment of debris movement was conducted to benefit rehabilitation efforts within the park. Approximately 180 acres of timber were affected as a result of the embankment failure flood.

Introduction

The Taum Sauk pump-storage hydroelectric power plant owned and operated by Ameren UE was completed in July, 1963, and went into commercial operation on December 20, 1963. After years of planning, Ameren UE chose 1,590-ft (foot) high Proffit Mountain in Reynolds County, Missouri, for the location of the power plant. The plant was named "Taum Sauk" after the legendary Indian chief who once ruled tribes in the area. The plant utilizes reversible turbines that operate as pumps. The pumps use power from other plants to pump water into an upper reservoir on top of Proffit Mountain during "off-peak" hours occurring nights and weekends. When electricity demand is high, the pumps become turbine-generators and the process is reversed as water is released from the upper reservoir to the lower reservoir through a 7,000-ft tunnel, producing electricity in the same manner as a conventional hydro-electric power plant. The approximate operating head between the lower and upper reservoir ranges from 776 to 860 ft (Hendron and others, 2006). Johnson's Shut-Ins State Park, managed by the Missouri Department of Natural Resources, exists along the East Fork Black River adjacent to Proffit Mountain (fig. 1). The term "Shut-Ins," defines an area where waters of the East Fork Black River become confined, or "shut-in," to a narrow channel approximately 1 mi (mile) downstream from State Highway N. With time, transported sand and gravel have produced unique erosional features such as small gorges, chutes, and potholes throughout the Shut-Ins.

At approximately 5:16 am on December 14, 2005, the embankment of the upper reservoir failed as water filled the reservoir during the "off peak" pumping cycle. A 680-ft wide breach of the 55-acre reservoir drained approximately 1.5 billion gallons of water down an intermittent stream valley along the western side of Proffit Mountain and into the East Fork Black River. The full breach developed within 25 minutes from the initial drop of the reservoir level (Hendron and others, 2006). The flood wave split at the base of Proffit Mountain, removing a residential structure from the foundation, washing a tractor trailer vehicle off of State Highway N, and damaging a U.S. Geological Survey (USGS) streamflow-gaging station located at the State Highway N crossing of East Fork Black River (fig. 2). The USGS streamflow-gaging station recorded the last stage at 5:15 am on December 14, 2005. The force of the flood wave stripped overburden from the western slope of Proffit Mountain, exposing bedrock and depositing material downstream (fig. 3). The embankment surrounding the kidney shaped upper reservoir is approximately 6,562-ft long and is composed of rock fill that is protected by a 10-in. (inch) thick concrete face on the upstream side (Hendron and others, 2006). Original drawings indicate an approximate 1.3:1 slope on the upstream and downstream face of the embankment with a 12-ft wide crest at an elevation of 1,589 ft. A 10-ft high, 1-ft thick concrete reinforced parapet wall extends the crest to an elevation of 1,599 ft, as originally constructed. The concrete parapet has settled 1 to 2 ft since 1963 (Hendron and others, 2006). Excavated rock primarily composed of rhyolite porphyry was used to construct the embankment.

Floods of large magnitude such as the one produced by the embankment failure disrupt ecological and fluvial systems by altering channel configurations, substrate, and sediment load and present unique challenges and opportunities to analyze and document flood characteristics, such as flood hydraulics and unit peak discharge within the surrounding watershed. To address this need, the USGS in cooperation with the Missouri Department of Natural Resources (MDNR) conducted a study on the East Fork Black River and Taum Sauk Creek at the Taum Sauk Pump Storage Facility near Lesterville, Missouri.

Purpose and Scope

The purpose of this report is to document the flood peak discharge, flood profiles, flood inundation, and debris movement as a result of the failure of the upper reservoir. This report presents flood frequency comparisons along the East Fork Black River and examines the impact of flooding for a hypothetical case in which the eastern embankment would fail, releasing flood waters into Taum Sauk Creek located on the east side of Proffit Mountain. One-dimensional dynamic wave unsteady flow models were used to route the embankment failure flood, thereby producing a flood hydrograph from the breach of the upper reservoir, down the western slope of Proffit Mountain, into the East Fork Black River, and further downstream to the spillway of the lower reservoir. One-dimensional steady-state simulations produced flood profiles that were used in developing inundation maps for flood frequency estimates along the East Fork Black River just upstream from State Highway N, downstream to the spillway of the lower reservoir. A quantitative approach was used to roughly estimate the volume of debris movement, and to examine debris impacts along the East Fork Black River and within the lower reservoir.

Description of the Study Area

The Taum Sauk pump-storage hydroelectric power plant is located in Reynolds County, Missouri, approximately 2 mi north of Lesterville and approximately 90 mi southwest of St. Louis. The study area resides among the St. Francois mountains in the Ozark Plateau physiographic region, which is heavily wooded and rugged with narrow valleys, dendritic (tree-shaped) drainage, and main channel gradients steeper than elsewhere in Missouri. Elevations in this region range from about 800 to 1,700 ft (Alexander and Wilson, 1995). The upper reservoir, on top of Proffit Mountain, has an average basin bottom elevation of approximately 1,505 ft. The lower reservoir is at the junction of the East Fork Black River and Taum Sauk Creek, and is impounded by a dam in the form of a concrete ogee spillway across the East Fork Black River (fig. 1). Normal operating pool elevations for the lower reservoir range from 736 to 748 ft (M. Menne, Ameren UE, oral commun., 2006).

Analyses along the western side of Proffit Mountain were conducted along an 8,400-ft reach of an intermittent stream valley from the breach of the upper reservoir down the mountain to its intersection with the East Fork Black River. Analyses along the East Fork Black River were conducted along a 27,000-ft reach from a location just upstream from State Highway N, to the spillway of the lower reservoir. Analyses along Taum Sauk Creek were conducted along a 19,000-ft reach from an upstream location perpendicular to the east embankment of the upper reservoir, downstream to the spillway of the lower reservoir.

A USGS streamflow-gaging station located on the downstream face of State Highway N over the East Fork Black River (fig. 1) has been in operation from October 2001 to September 2002, and from October 2003 to the current year (2006). The

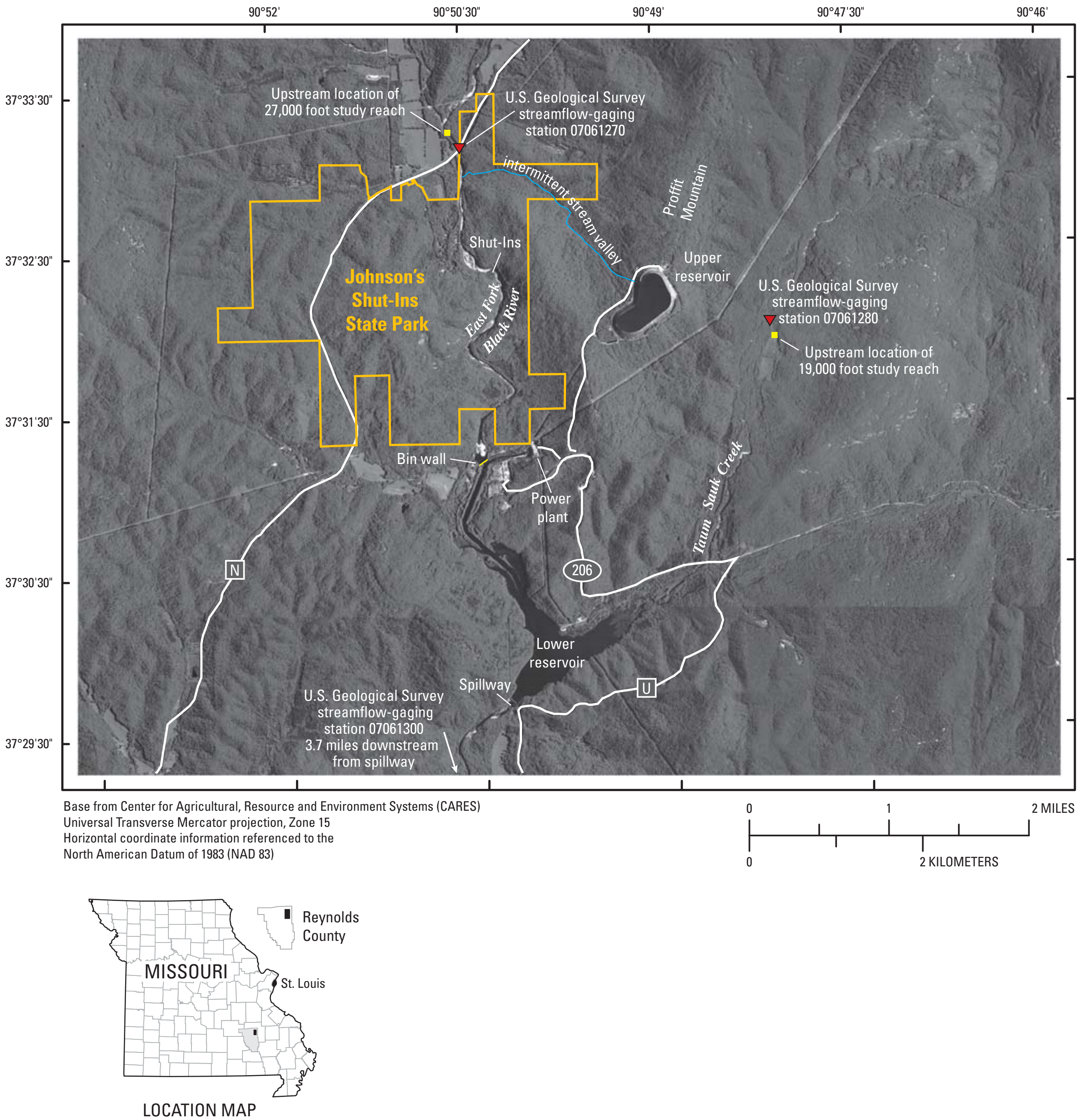
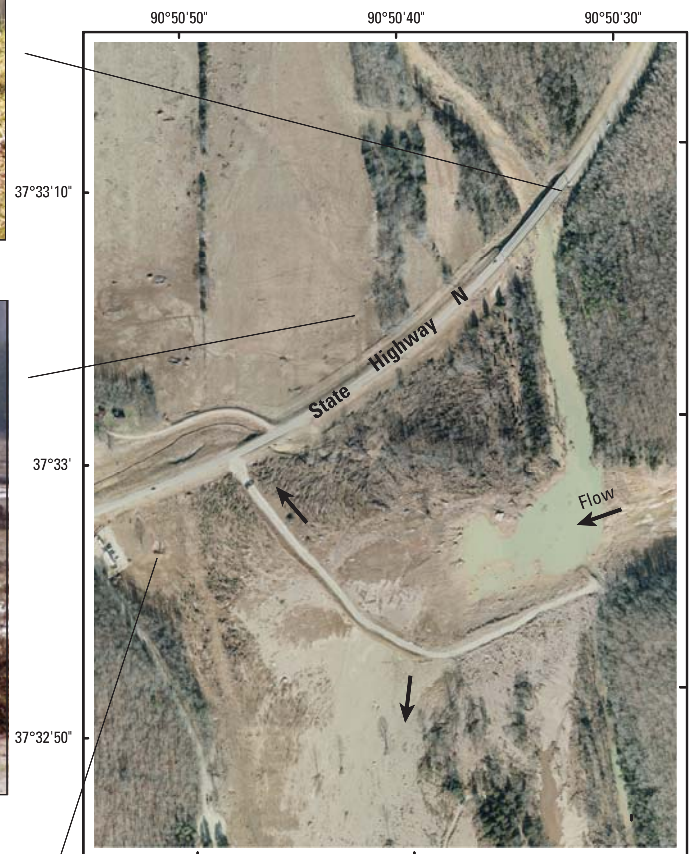


Figure 1. Location of Johnson's Shut-Ins State Park boundary and Taum Sauk pump-storage hydroelectric power plant facility.

U.S. Geological Survey streamflow-gaging station and debris accumulation.

Tractor trailer washed off of State Highway N. Note the high water mark on the cab of the truck (photograph courtesy of Ken Beck, Reynolds County Courier, 2005).

Exposed foundation of park superintendent residence.



Base from Surdex, Inc., proprietary to MACTEC Engineering and Consulting, Inc.
One-half foot pixel resolution, January 2006
Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)

0 0.06 0.12 MILES
0 0.06 0.12 KILOMETERS

Figure 2. Flood wave damage at base of Proffit Mountain and State Highway N.

Figure 3. Stripped overburden as a result of flood wave force on the western slope of Proffit Mountain.

maximum recorded gage height of 838.6 ft occurred May 12, 2002, before a developed stage-discharge relation (Hauck and Nagel, 2002). The annual mean discharge recorded for the period of record is 79.4 ft^3/s (cubic feet per second) (Hauck and Nagel, 2004).

Acknowledgments

The author thanks all personnel from the Missouri Department of Natural Resources that were involved with data collection, coordination, or provided guidance. The author also thanks Ameren UE and MACTEC Engineering and Consulting, Inc. for data sharing and data-collection support.

Reconnaissance and Data Collection

The failure of the upper reservoir presented a historic opportunity to conduct field assessments and gather data. Within hours of the failure, field crews were on site to document damage and monument high water marks from the upper reservoir breach, down along the western side of Proffit Mountain, to a junction with the East Fork Black River. In addition, reconnaissance and high water monumentation were performed along the East Fork Black River from a location upstream from State Highway N, to the lower reservoir spillway (fig. 4). Digital film footage was used to document flood damage and help develop a conceptualization of flow behavior from the breach down to the lower reservoir.

A double peak was evident along the East Fork Black River during the monumentation of high water marks. The larger peak was from the part of the flood wave that flowed downstream after entering the floodplain at the base of Proffit Mountain. The second smaller peak was from a smaller part of the flood waters that initially moved upstream, overtopping a substantial part of State Highway N, submerging a culvert opening, and flowing upstream through the bridge over the East Fork Black River. The smaller secondary peak resulted when the flood waters above State Highway N flowed back through the culvert, bridge opening, and continued through Johnson's Shut-Ins State Park. Areas of super-elevated water surfaces produced by centrifugal forces were evident from high water marks and the debris that was produced by the flow as it rushed down Proffit Mountain, built up against the opposing valley wall from the base of Proffit Mountain, and meandered downstream along the East Fork Black River. Left and right bank water-surface elevation differences determined from high water marks ranged as high as 35 to 40 ft down Proffit Mountain, 12 to 20 ft across the valley floor at the base of Proffit Mountain, and as much as 7 ft through the Shut-Ins.

Aerial Topographic Survey

Light Detection and Ranging (LiDAR) derived mass points at an approximate ground spacing of 2.3 ft or better throughout a 31.5 mi^2 (square mile) area (Sanborn Inc., written commun., 2005) were collected to define the land surface and structures. A digital elevation model (DEM) was completed at a vertical accuracy of 0.5 ft Root Mean Square Error (RMSE) and a horizontal accuracy of 1.64 ft (RMSE) (Brostuen, 2006). The arrival of the LiDAR aircraft, data capture, and data completion occurred on December 16, 2004. The completed bald-earth DEM was available within 2 weeks of the original data acquisition.

Geo-referenced and attributed contours were derived from the LiDAR data. Cross sections were cut from contours perpendicular to conceptualized flow paths and used for all hydraulic analyses. All cross sections provided necessary geometry for hydraulic modeling and indirect determinations of discharge using the slope-area method. Substantial modifications to channel and floodplain geometry from the flood were assumed to have occurred on the rising limb of the hydrograph (before the peak); therefore, all indirect and hydraulic analyses of peak discharge used post-flood geometry. Contour data also served as the foundation for inundation mapping within this study. In addition, LiDAR data supported spatial and volumetric analysis of overburden and debris by differencing the LiDAR DEM with a preexisting 10-meter DEM based on 1:24,000-scale topography.

Ground Survey

The Missouri Department of Natural Resources, Division of Geology and Land Survey (MDNR-DGLS), deployed staff to correlate approximately 885 monumented high water marks to datum. Global positioning system (GPS) surveying was used to establish survey control points throughout the reach that were referenced to horizontal and vertical datum. The majority of control was post processed using the National Geodetic Survey Online Positioning Users Service and local High Accuracy Network (HARN) stations (O. Lashley, Missouri Department of Natural Resources, Division of Geology and Land Survey, oral commun., 2006). Surveying using total station instrumentation established positioning and elevation from control points to high water marks.

Supplemental topographic surveys were conducted along Taum Sauk Creek, outside of the eastern limit of LiDAR data capture. Topographic surveys along Taum Sauk Creek also utilized GPS and total station surveying, and were conducted to establish cross sections necessary for modeling and inundation mapping (fig. 5).

Lower Reservoir Bathymetry Survey

The embankment failure flood had large hydraulic head differences that imposed high shear stress that subsequently contributed to the transport of sediment and debris into the lower reservoir. An area/capacity table produced by a bathymetric survey provided volumetric analysis, which helped in determining the impact of sedimentation.

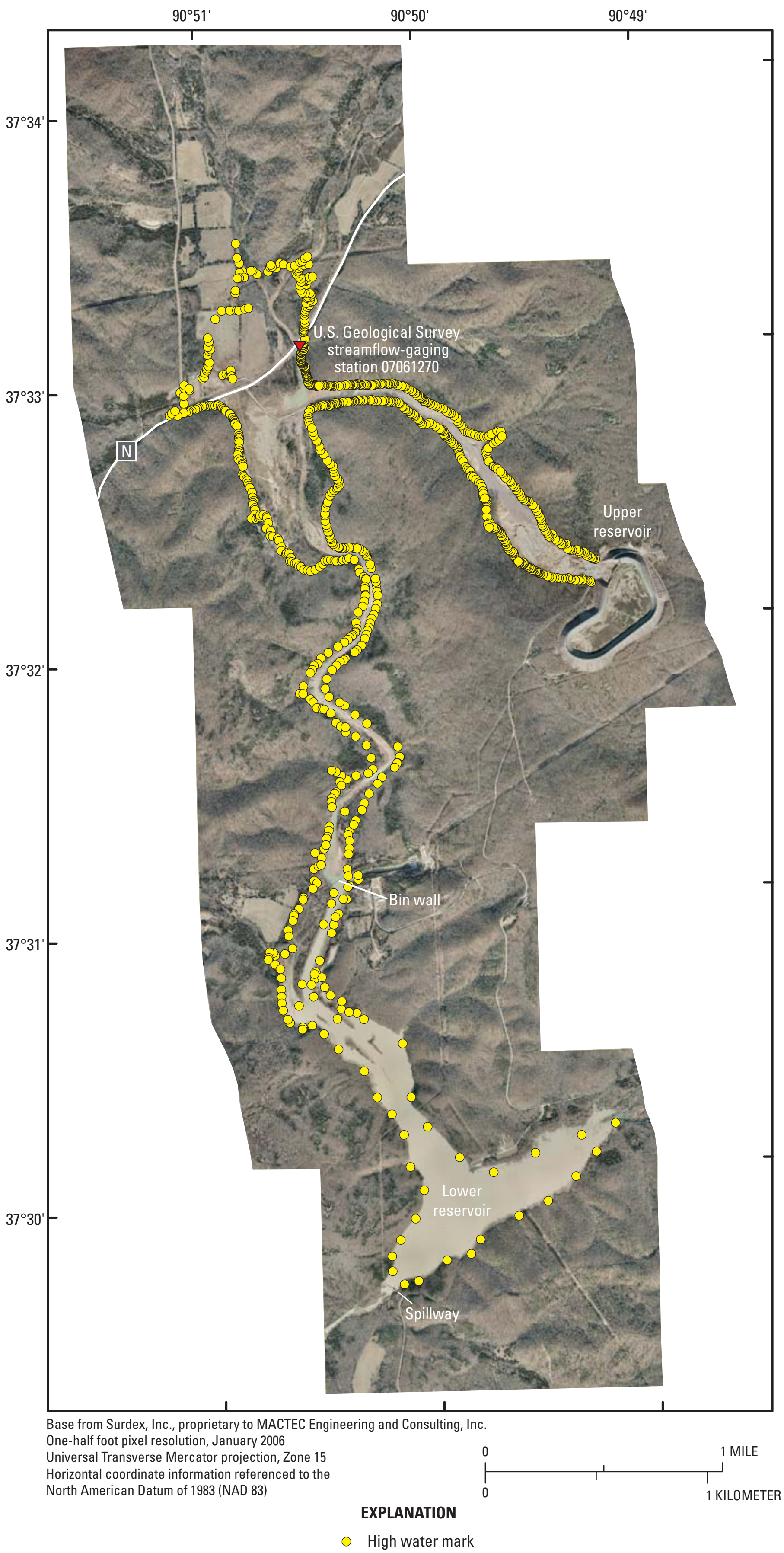


Figure 4. Aerial image flown after embankment failure flood (December 14, 2005) with location of high water marks.

Global Positioning System (GPS) static session surveying.

Rod height calibration for total station instrument surveying.

Figure 5. Topographic survey along Taum Sauk Creek, February 6, 2006.

A bathymetric survey of the lower reservoir was conducted between December 22, 2005, and December 23, 2005, using a survey-grade echo sounder with a 200 kHZ transducer. The echo sounding device was used to collect water depths and was combined with an AgGPS receiver that used permanent reference base stations to differentially correct a horizontal position (Wilson and Richards, 2006). To ensure quality data collection, the echo sounder was calibrated twice per day by water temperature and plate measurements. Water temperature was used to identify the speed at which a sound wave traveled through the water column. A plate was placed at a known depth below the transducer and calibrated to record this depth. The plate was then placed at a much deeper elevation and the speed of sound value was adjusted until the transducer recorded the exact depth (+/- 0.1 ft) (Wilson and Richards, 2006). The horizontal positioning accuracy of the echo sounder using an AgGPS receiver is better than 3.28 ft according to manufacturer's specifications (Trimble, 1999).

The bathymetric survey utilized specialized navigation software "HyPack" to layout survey transects. HyPack, used together with GPS, allows vessel position to be tracked relative to transects, thereby ensuring optimal data capture. Approximately 318,000 data points were collected. Data points were collected every 0.66 ft along each transect and each transect was spaced approximately 50 ft apart. Bathymetry of the lower reservoir was merged with LiDAR data exposed at the shoreline. An area/capacity table was combined with a 2-ft contour map (fig. 6). The bathymetric survey was conducted with quality-control points that were intersected with the bathymetric surface. Based on any random selected test data set, 95 percent of those points were within +/- 1.45 ft of the "true" elevation (Wilson and Richards, 2006). Quality control points also were intersected with mapped contours. Based on any random selected test data set, 95 percent of those points were within 3.38 ft of the "true" contour elevation. The National Standard for Spatial Data Accuracy (NSSDA) is an alternative standard for map accuracy published by the Federal Geographic Data Committee (FGDC) that provides a method to compute the vertical RMSE at the 95 percent confidence level under the assumption that error is normally distributed (Wilson and Richards, 2006). The NSSDA vertical accuracy (Federal Geographic Data Committee, 1998) is computed using the following equations:

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^{n} (Z_{data_i} - Z_{check_i})^2}{n}} \qquad (1)$$

where

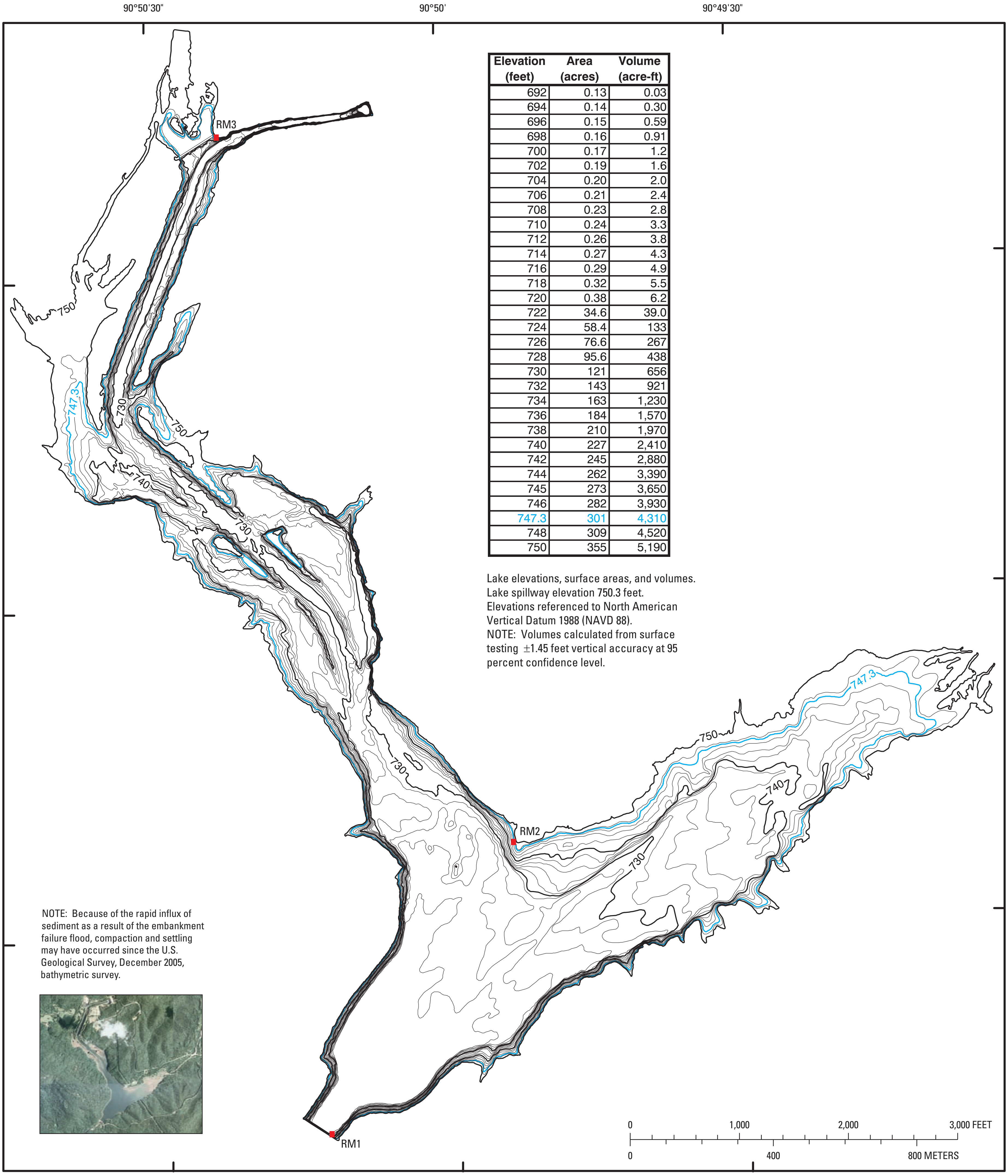
- $RMSE_z$ is the Vertical Root Mean Square Error;
- Z_{data_i} is the vertical coordinate of the i^{th} check point in the data set;
- Z_{check_i} is the vertical coordinate of the i^{th} check point in the quality assurance data set;
- i is an integer from 1 to n; and
- n is the number of points being checked.

$$A_z = 1.960 * RMSE_z \qquad (2)$$

where

- A_z is the fundamental vertical accuracy calculated at the 95-percent confidence level.

To analyze the impacts of sedimentation into the lower reservoir from the embankment failure flood, the bathymetric surface was differenced from a previous bathymetric surface produced April 18, 2005, through April 21, 2005. The previous bathymetric surface was obtained from a previous investigation and was developed using approximately 23,800 data points that were collected at approximately 16-ft intervals along transects



Elevation (feet)	Area (acres)	Volume (acre-ft)
692	0.13	0.03
694	0.14	0.30
696	0.15	0.59
698	0.16	0.91
700	0.17	1.2
702	0.19	1.6
704	0.20	2.0
706	0.21	2.4
708	0.23	2.8
710	0.24	3.3
712	0.26	3.8
714	0.27	4.3
716	0.29	4.9
718	0.32	5.5
720	0.38	6.2
722	34.6	39.0
724	58.4	133
726	76.6	267
728	95.6	438
730	121	656
732	143	921
734	163	1,230
736	184	1,570
738	210	1,970
740	227	2,410
742	245	2,880
744	262	3,390
745	273	3,650
746	282	3,930
747.3	301	4,310
748	309	4,520
750	355	5,190

Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)

EXPLANATION

— 750 — **Bathymetric contour**—Shows elevation of the reservoir bottom. Contour interval 2 feet. Contours tested 3.38 feet vertical accuracy at 95 percent confidence level

— 747.3 — **Water surface**—Shows approximate elevation of water surface, December 20 to 22, 2005

■ RM2 **U. S. Geological Survey reference marker and identifier**—RM1-Chiseled arrow on northeast corner of concrete outlet structure at dam. Elevation 750.26 feet. RM2-Chiseled arrow on downstream curb at boat ramp. Elevation 747.47 feet. RM3-Chiseled arrow on downstream corner of left abutment of sediment dam. Elevation 760.27 feet

Figure 6. Bathymetric map for lower Taum Sauk reservoir near Lesterville, Missouri.

that were spaced approximately 165 ft (MACTEC, Inc., written commun., 2006). An area/capacity difference table was combined with a bathymetric difference map (fig. 7). The most substantial difference (147 acre-ft) was noted at an elevation of 730 ft. It should further be noted that because of a rapid influx of sediments caused by the embankment failure flood, settling and compaction may have occurred since the December 2005 bathymetric survey.

Peak Discharge

Peak discharge is a fundamental hydrologic parameter used to quantify the magnitude of flood events. It is used as a design variable for hydraulic planning and flood frequency estimates. The embankment failure flood can be analyzed to quantify the volume and rate of water and potentially predict erosion and sediment transport. Peak discharge estimates also can be used to supplement hydraulic models, better quantifying the results. Indirect measurements of peak discharge make use of the energy equation and incorporate general factors such as the physical characteristics of the channel and the water-surface elevations at the time of peak stage, and hydraulic factors such as Manning's roughness coefficients and discharge coefficients based on open channel physical characteristics, water-surface elevation, and discharge (Rantz, 1982).

Discharge Analyses along Proffit Mountain

The unsteady nature of flow surging down Proffit Mountain attenuated the peak discharge. Two indirect methods of estimating peak discharge were evaluated. The first method, the reservoir-volume method integrated 5-second interval water-elevation data provided by Ameren UE in the upper reservoir during the time of failure, with reservoir geometry from LiDAR data to produce a volume per time (flow) hydrograph (fig. 8). Wave action coupled with short duration (5 second) readings produced scatter in the drawdown curve. As a result, elevation data were averaged over a 1-minute timeframe to reduce the scatter of the computed discharge data. For each averaged elevation value provided in the drawdown curve, an area and volume was produced per time. The peak of the developed hydrograph was 289,000 ft^3/s.

The second method involved a slope-area computation and was used to verify the previous method using reservoir geometry. When conducting slope-area computations, the reach length must be long enough to develop a fall that will exceed the range of error because of uncertainties regarding the computation of velocity head and interpretation of the hydraulic profile using high water marks (Dalrymple and Benson, 1967). Criteria developed by Dalrymple and Benson states that the length of a reach selected for a slope-area computation should be approximately 75 times the mean depth in the channel. To ensure this criteria, the slope-area reach had to range from 1,500 to 1,800 ft long. Peak discharge free fall down the mountainside limited the reach length of constant discharge. In addition, a shorter reach length ensured flow behavior as gradually varied, an assumption in the slope equations. To best capture the peak, the "75 times the mean depth" criteria was not strictly adhered to. A 286-ft reach with 10.4 ft of fall was analyzed where the reach was straight, contracting, and high water marks did not depict substantial surge (fig. 9). The computed peak discharge was 297,000 ft^3/s. The Froude number can be described as a dimensionless parameter that measures the ratio of the inertial force on a fluid element to the weight of a fluid element. In open channel hydraulics, the Froude number often is used to differentiate downstream controlled subcritical flow ($F < 1$) from upstream controlled supercritical flow ($F > 1$). The slope-area reach represented supercritical flow, as shown in table 1.

Many different slope-area computation attempts were conducted along Proffit Mountain. Errors representing negative fall were common because of attenuation and surge of peak discharge. The slope-area method relies on the energy equation and assumes a hydrostatic pressure distribution that is difficult to satisfy for unsteady flow where free fall is common. The slope-area computation was within 3 percent of the reservoir-volume method using elevation data.

Slope-Area Analyses along the East Fork Black River

Two slope-area analyses of estimating peak discharge were evaluated along the East Fork Black River downstream from the Shut-Ins. Both computations were conducted along a reach that was straight and contracting. The peak discharge associated with the "wall of water" coming down the East Fork Black River attenuated substantially at the Shut-Ins, thereby requiring a shorter slope-area reach to capture the peak. The first slope-area analysis was located approximately 6,100 ft downstream from State Highway N (fig. 10). The 584-ft reach had 4.5 ft of fall. The computed peak discharge was 90,000 ft^3/s. The slope-area reach represented subcritical flow ($F < 1$), as shown in table 2.

The second slope-area analysis was located approximately 9,430 ft downstream from State Highway N (fig. 11) and was developed to verify the first analysis. The 459-ft reach length had 2.2 ft of fall. The computed peak discharge was 100,000 ft^3/s. The slope-area reach represented subcritical flow ($F < 1$), as shown in table 3. The assumed peak flow along the East Fork Black River was averaged to 95,000 ft^3/s +/- 5,000 ft^3/s based on the two slope-area analyses.

Dynamic Wave Analyses

To adequately assess peak-flow volume and time along the western side of Proffit Mountain, dynamic wave unsteady flow models Dam Break (DAMBRK) and Unsteady NETwork (UNET) were used to route the flood wave. DAMBRK is a dynamic wave unsteady flow routing model that was developed by the National Weather Service and combined with a graphical user interface developed by BOSS International, Inc. (2000). A

DAMBRK model was developed to route the embankment failure discharge hydrograph down Proffit Mountain to the floodplain of the East Fork Black River. The UNET is a dynamic wave unsteady flow routing model developed by the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC). The UNET executable is integrated into a graphical user interface, Hydrologic Engineering Center - River Analysis System (HEC-RAS), also developed by the USACE HEC. A UNET model was developed as a supplemental effort in routing the embankment failure hydrograph down Proffit Mountain, to a junction with the East Fork Black River, and continuing downstream to the spillway of the lower reservoir. Wave propagation inherent to both DAMBRK and UNET can be described by the one-dimensional Saint-Venant equations based on continuity and momentum (Chagas and Souza, 2005).

Continuity Equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{3}$$

Momentum Equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\left(\frac{\partial y}{\partial x} - S_0\right) + gAS_f = 0 \tag{4}$$

where

- Q is the discharge;
- A is the cross-sectional area of flow in square feet (ft^2);
- x is the longitudinal distance along the channel, in feet (ft);
- t is the time, in seconds (s);
- y is the water-surface elevation, in feet (ft);
- g is the acceleration because of gravity, 32.2 foot per square second (ft/s^2);
- S_0 is the channel bottom slope, in foot per foot (ft/ft); and
- S_f is the energy grade line slope, in foot per foot (ft/ft).

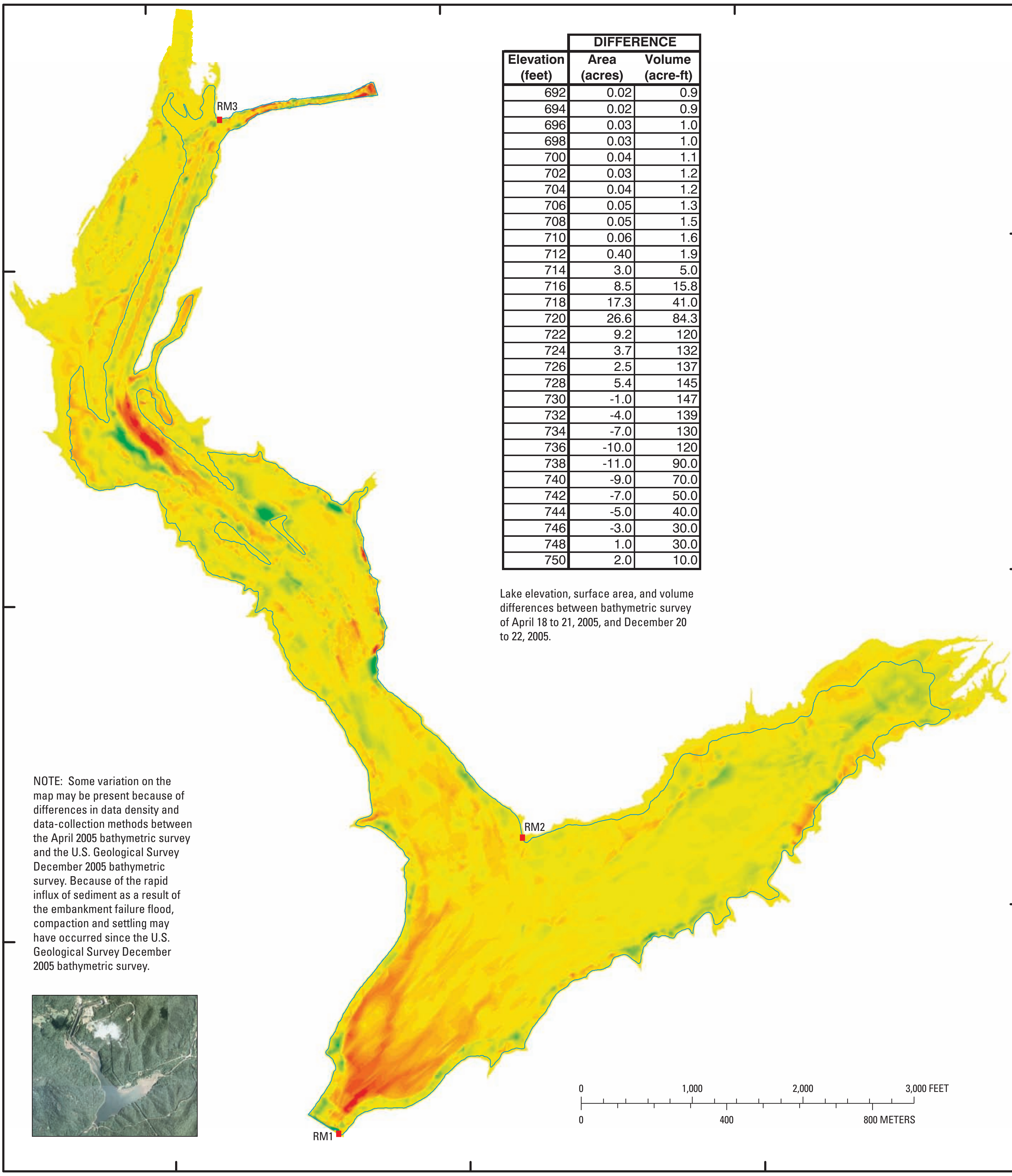
The dynamic wave is a wave classification that considers all the terms in the momentum equation (Chagas and Souza, 2005), an equation that represents the physical movement of water. The continuity equation preserves the water volume in the channel (Sylvestre and Sylvestre, 2003). Dynamic wave unsteady flow routing models used in this study allow the flood wave to attenuate upstream and downstream, in contrast to kinematic wave models that allow the wave to move in the downstream direction only (Sylvestre and Sylvestre, 2003). In addition to water movement, a comparison between kinematic and dynamic wave properties can be described on a rating curve where kinematic models assume uniform flow, depicted by a straight line, and dynamic models accommodate unsteady flow, as shown by hysteresis (loop effect) in a stage-discharge relation (fig. 12). Dynamic wave unsteady flow routing models DAMBRK and UNET used the discharge hydrograph developed in figure 8 for inflow simulations.

During catastrophic flood events where physical channel characteristics are submerged and a substantial amount of material is in transport, roughness-verification studies conducted in relatively stable and favorable environments may have a limited impact in providing guidance in selecting Manning's roughness coefficients (Costa, 1994). Guidance in selecting Manning's roughness coefficients for the DAMBRK and UNET models was provided by Barnes (1967) and Arcement and Schneider (1989).

DAMBRK Model Setup

Problem specification option 7 was chosen in DAMBRK to route unsteady flow down a channel valley based on an input discharge hydrograph. This option does not allow the program to compute an outflow hydrograph as a result of the upper reservoir breach, and furthermore restricts including dams or bridges along the downstream valley. An average downstream channel slope of 44 ft/mi (feet per mile) was used to compute the tailwater elevation of 852.8 ft by using the Manning's equation, thereby satisfying the downstream boundary condition. Cross sections initially were added at substantial breaks in slope. DAMBRK requires each cross section to be input as an elevation-top width pair, resulting in geometric symmetry. The changing slope down Proffit Mountain was represented by two sub-reaches; the first sub-reach represented a slope approximately 0.2 ft/ft (foot per foot), or 1,056 ft/mi, from the breach to a location approximately 440 ft downstream. The slope of the remaining sub-reach was approximately 0.03 ft/ft, or about 160 ft/mi, to the junction with the East Fork Black River. Additional cross sections were added, ensuring a positive slope at the downstream end for initial conditions and abiding by a "rule of thumb" that allows cross-section top widths to increase by 100 percent or decrease by 50 percent from section to section (BOSS International, Inc., 2000). A total of 11 cross sections were input, and additional cross sections were interpolated by the model to ease the transition of flow along the mountainside to the junction with the East Fork Black River.

Composite roughness values ranging from 0.095 at smaller depths to 0.05 at greater depths were used to characterize flow resistance. An initial time step of 0.001 hr (hour) (3.6 seconds) was small enough to capture the peak discharge in the input hydrograph. A mixed flow option was used within DAMBRK, which identifies an initial flow and water surface at time = 0, in addition to categorizing subcritical and supercritical flow based on the Froude number at each cross section. To help mitigate model divergence associated with a dramatic change in channel bed slope, the water surface-elevation convergence criteria was raised to 0.05 ft from the default value at 0.01 ft. Final model results indicated a -0.65 percent loss in conserving mass as a percentage of inflow volume.



Elevation (feet)	DIFFERENCE Area (acres)	Volume (acre-ft)
692	0.02	0.9
694	0.02	0.9
696	0.03	1.0
698	0.03	1.0
700	0.04	1.1
702	0.03	1.2
704	0.04	1.2
706	0.05	1.3
708	0.05	1.5
710	0.06	1.6
712	0.40	1.9
714	3.0	5.0
716	8.5	15.8
718	17.3	41.0
720	26.6	84.3
722	9.2	120
724	3.7	132
726	2.5	137
728	5.4	145
730	-1.0	147
732	-4.0	139
734	-7.0	130
736	-10.0	120
738	-11.0	90.0
740	-9.0	70.0
742	-7.0	50.0
744	-5.0	40.0
746	-3.0	30.0
748	1.0	30.0
750	2.0	10.0

Lake elevation, surface area, and volume differences between bathymetric survey of April 18 to 21, 2005, and December 20 to 22, 2005.

NOTE: Some variation on the map may be present because of differences in data density and data-collection methods between the April 2005 bathymetric survey and the U.S. Geological Survey December 2005 bathymetric survey. Because of the rapid influx of sediment as a result of the embankment failure flood, compaction and settling may have occurred since the U.S. Geological Survey December 2005 bathymetric survey.

Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)

EXPLANATION

Bathymetric surface difference—Change between the bathymetric survey of April 18 to 21, 2005, and December 20 to 22, 2005; >, greater than

Increase, in feet	Decrease, in feet
>9	>9
>8 to 9	8 to 9
>7 to 8	>7 to 8
>6 to 7	>6 to 7
>5 to 6	>5 to 6
>4 to 5	>4 to 5
>3 to 4	>3 to 4
>2 to 3	>2 to 3
>1 to 2	>1 to 2
>0 to 1	>0 to 1

Water Surface—Shows approximate location of water surface, December 20 to 22, 2005

RM1 **U. S. Geological Survey reference marker and identifier**—RM1-Chiseled arrow on northeast corner of concrete outlet structure at dam. Elevation 750.26 feet. RM2-Chiseled arrow on downstream curb at boat ramp. Elevation 747.47 feet. RM3-Chiseled arrow on downstream corner of left abutment of sediment dam. Elevation 760.27 feet

Figure 7. Bathymetric surface difference map for lower Taum Sauk reservoir near Lesterville, Missouri.

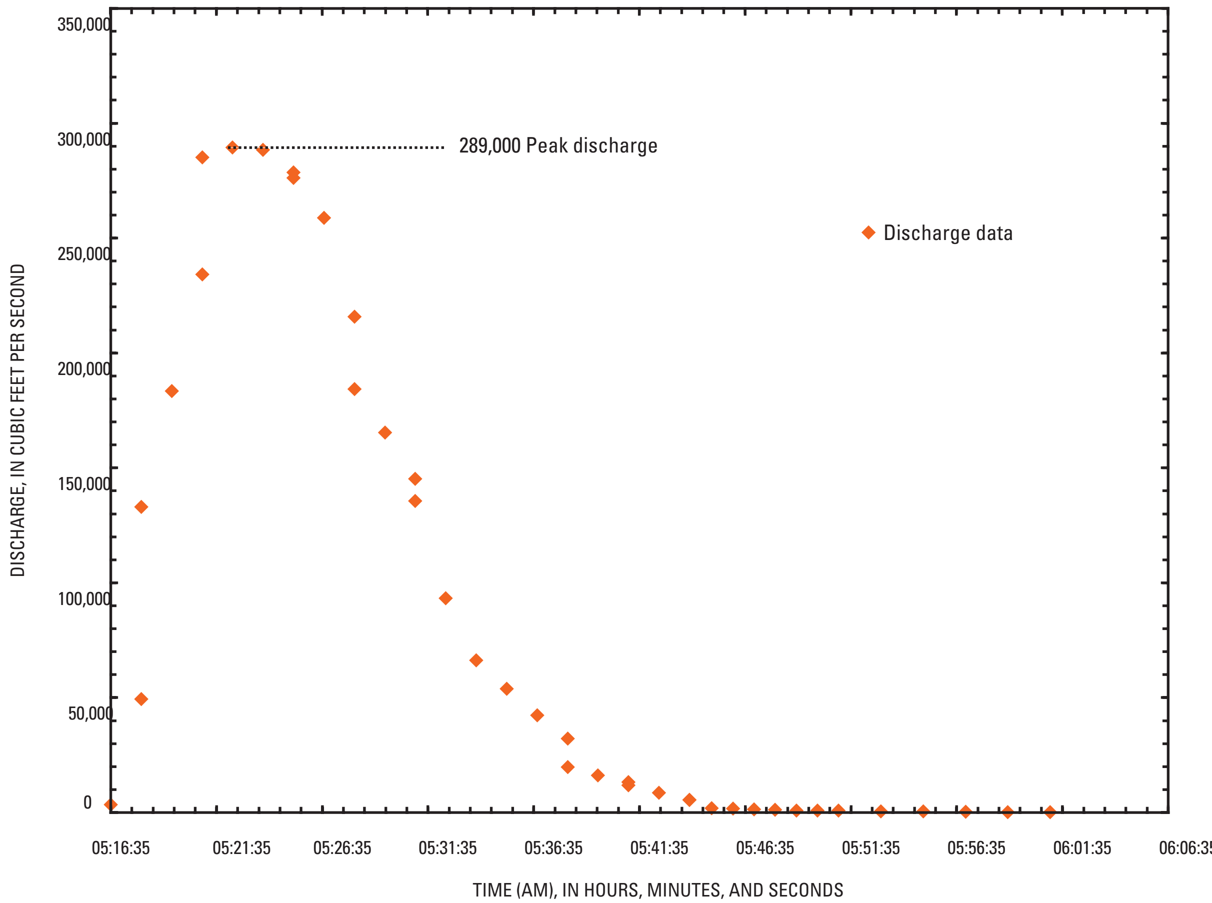


Figure 8. Hydrograph from volume analysis of upper reservoir embankment failure.

Table 1. Cross-section properties for a slope-area computation along the western side of Proffit Mountain.

[ft, feet; ft^2, square feet; ft/s, feet per second; F, dimensionless]

River station (fig. 9)	Water-surface elevation (ft)	Manning's roughness (n)	Area (ft^2)	Top width (ft)	Wetted perimeter (ft)	Velocity (ft/s)	Froude number (F)
21	914.1	0.08 –0.125	9,920	476	483	30.0	1.16
21.5	918.1	.08 –.125	11,200	507	515	26.7	1.00
22	918.2	.08 –.125	10,900	501	511	27.4	1.04
22.33	921.2	.08 –.125	10,400	484	493	28.6	1.08
22.66	923.6	.08 –.125	9,780	459	468	30.5	1.16
23	924.5	.08 –.125	8,910	427	438	33.4	1.29

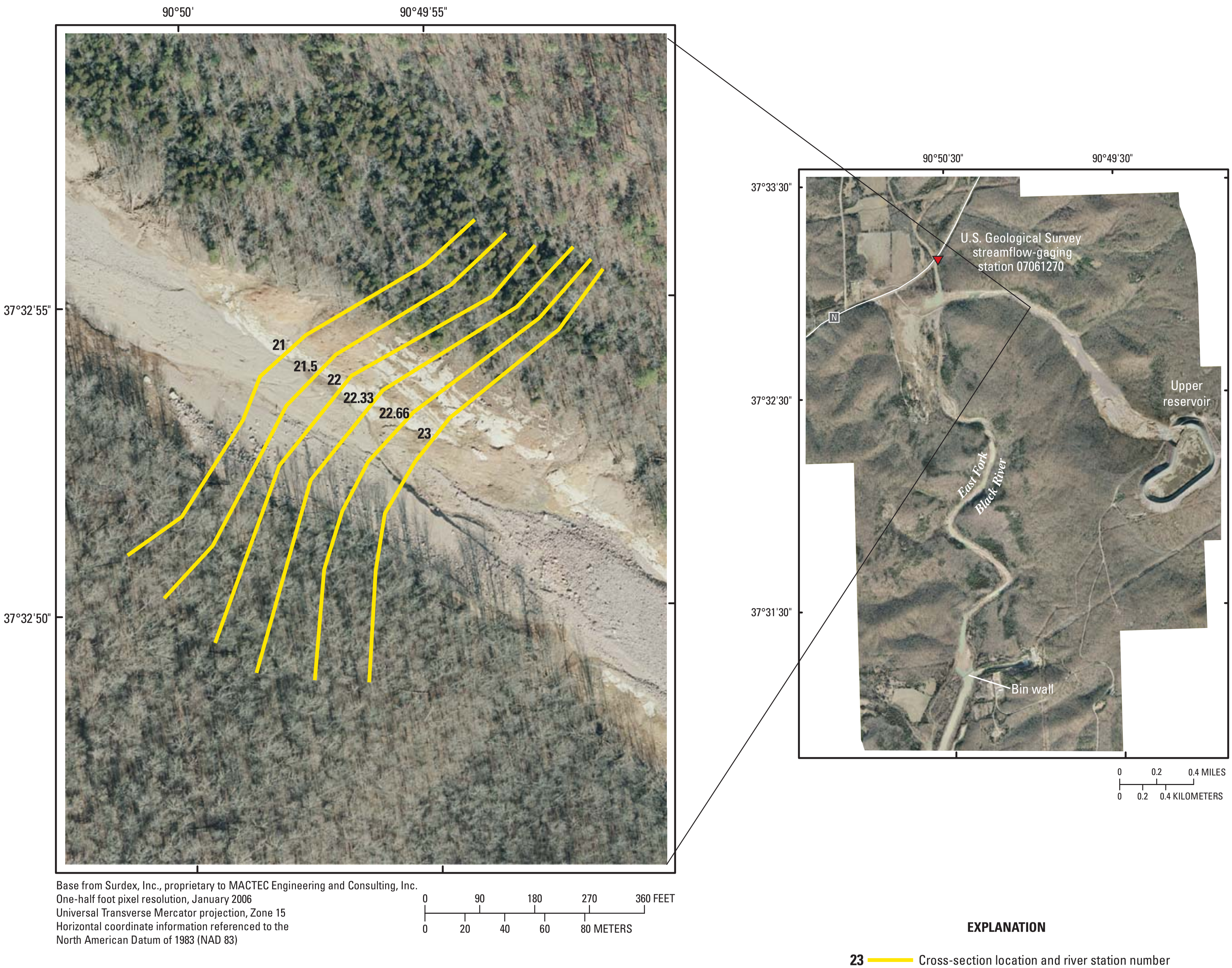


Figure 9. Cross-section location of slope-area computation along the western side of Proffit Mountain.

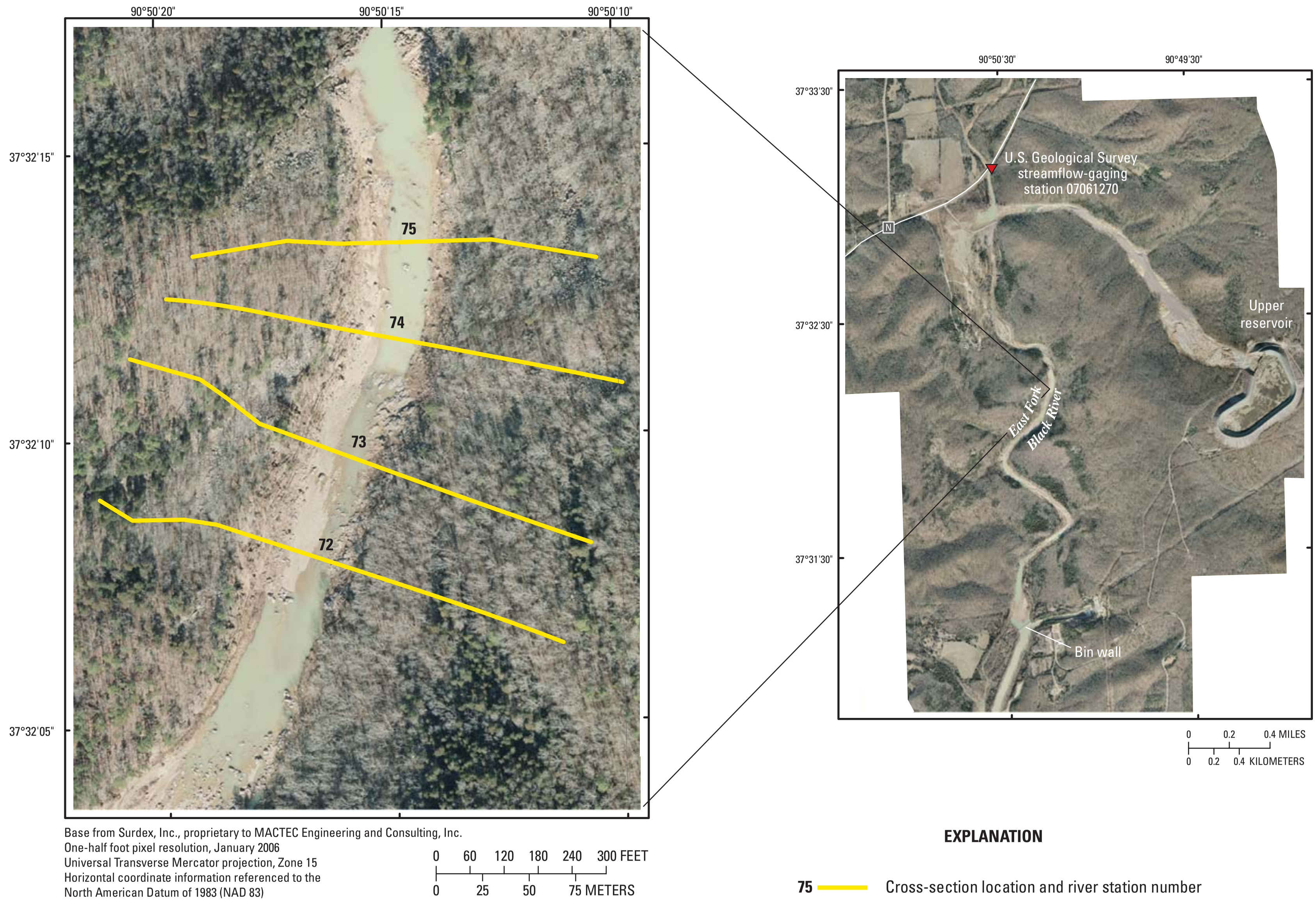


Figure 10. Cross-section location of slope-area computation along the upper East Fork Black River.

Table 2. Cross-section properties for a slope-area computation along the East Fork Black River approximately 6,100 feet downstream from State Highway N.

[ft, feet; ft^2, square feet; ft/s, feet per second; F, dimensionless]

River station (fig. 10)	Water-surface elevation (ft)	Manning's roughness (n)	Area (ft^2)	Top width (ft)	Wetted perimeter (ft)	Velocity (ft/s)	Froude number (F)
72	804.5	0.05–0.088	6,210	346	354	14.4	0.60
73	806.2	.05–.088	6,130	329	336	14.6	.60
74	805.5	.05–.09	5,410	286	295	16.6	.67
75	809.0	.05–.09	6,110	283	294	14.7	.56

Table 3. Cross-section properties for a slope-area computation along the East Fork Black River approximately 9,430 feet downstream from State Highway N.

[ft, feet; ft^2, square feet; ft/s, feet per second; F, dimensionless]

River station (fig. 11)	Water-surface elevation (ft)	Manning's roughness (n)	Area (ft^2)	Top width (ft)	Wetted perimeter (ft)	Velocity (ft/s)	Froude number (F)
52	782.2	0.045–0.115	11,700	963	976	8.5	0.43
52.16	782.2	.045–.115	11,400	965	975	8.7	.45
52.33	782.3	.045–.115	11,100	967	973	9.0	.47
52.50	782.4	.045–.115	10,800	960	964	9.2	.48
52.66	782.4	.045–.115	10,600	944	949	9.4	.50
52.83	782.4	.045–.115	10,400	938	944	9.6	.51
53	782.5	.045–.115	10,200	939	945	9.8	.53
53.25	782.9	.045–.115	9,760	894	899	10.2	.55
53.5	783.4	.045–.115	9,450	849	853	10.6	.56
53.75	783.8	.045–.115	9,070	803	807	11.0	.58
54	784.4	.045–.115	8,800	757	761	11.3	.59

UNET Model Setup

The UNET model used three reaches to represent the channel from the embankment failure to the lower reservoir on the East Fork Black River. The first reach along Proffit Mountain began just below the breach of the upper reservoir and ended at the junction with the East Fork Black River. The second reach along the East Fork Black River began approximately 760 ft upstream from State Highway N, and ended downstream at the junction with the Proffit Mountain reach. The third reach along the East Fork Black River began at the junction and ended at the spillway of the lower reservoir. The model incorporated 42 cross sections along the first reach, 5 cross sections along the second reach, and 109 cross sections along the third reach. All cross sections were taken directly from pre- and post-processing software known as BOSS RiverCAD (BOSS International, Inc., 2000).

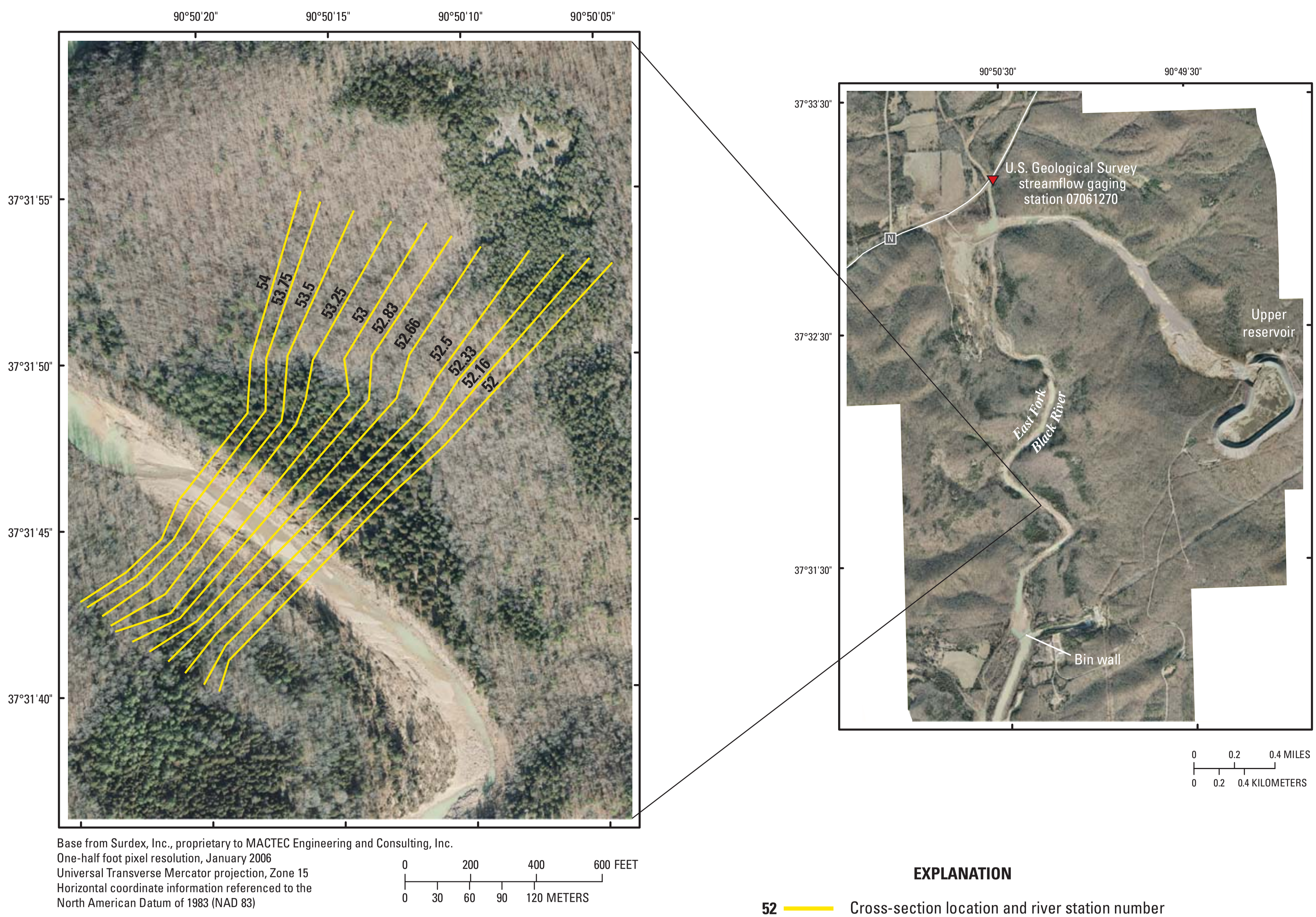


Figure 11. Cross-section location of slope-area computation along the lower East Fork Black River.

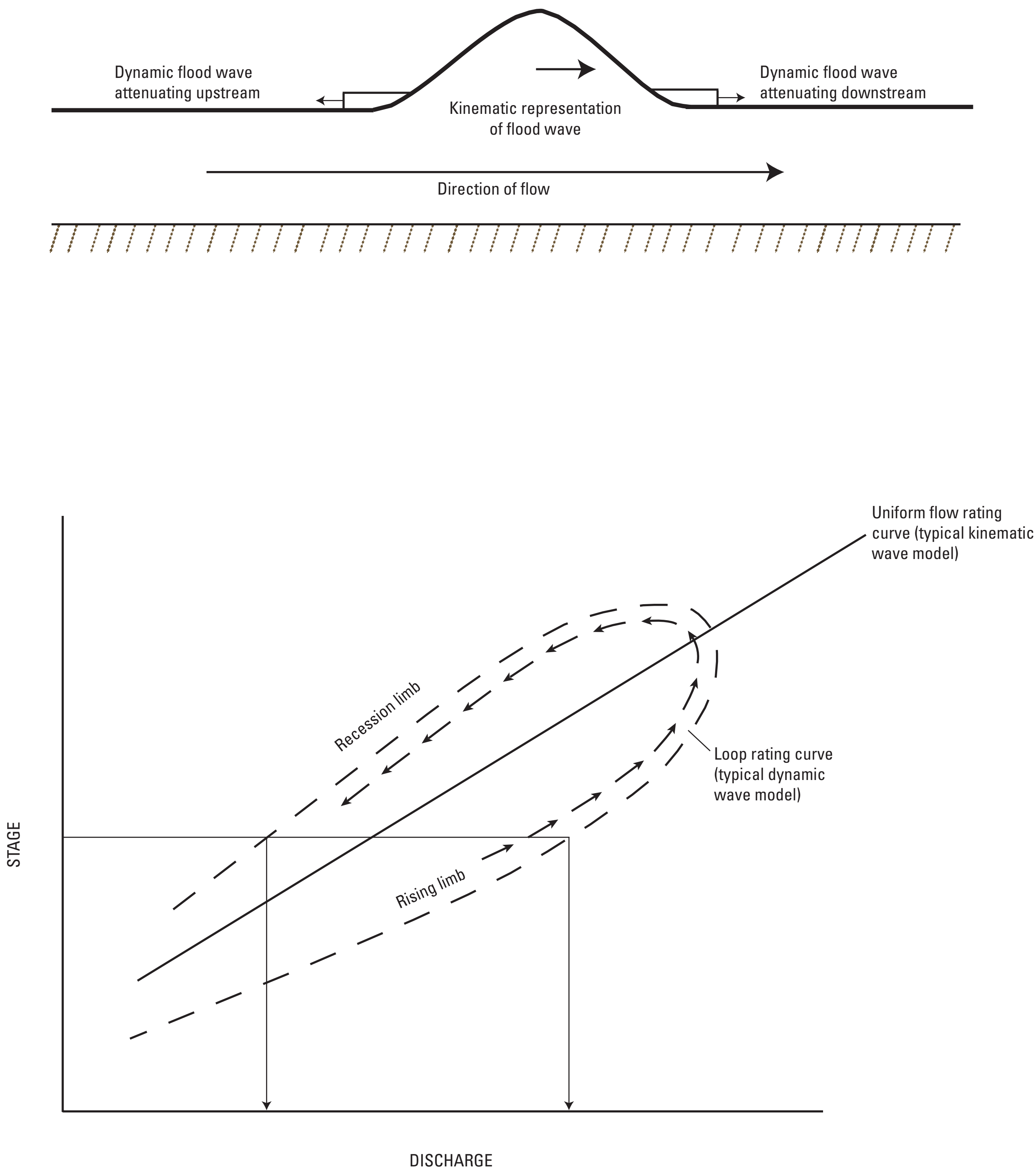


Figure 12. Dynamic and kinematic flood-wave movement and rating-curve description.

Two hydraulic structures and one storage area were developed for the UNET model. The State Highway N crossing and a "bin wall" (fig. 1) used to prevent debris and sediment from entering the lower reservoir were simulated as a bridge and weir, respectively, in the model. The east arm (Taum Sauk Creek) of the lower reservoir was modeled as a storage area. Manning's roughness values along the Proffit Mountain reach ranged from 0.08 to 0.125. Roughness values ranged from 0.045 to 0.125 along the East Fork Black River down to the lower reservoir. Roughness values representing the basin of the lower reservoir ranged from 0.03 to 0.045. Coefficients used to accommodate energy losses within a reach ranged from 0.1 to 0.5 for contraction and 0.2 to 0.5 for expansion along the Proffit Mountain reach and the East Fork Black River. An initial time step of 0.0028 hrs (10 seconds) was optimal in ensuring model convergence and capture of the peak discharge within the input hydrograph.

A mixed flow regime was selected for UNET model runs. The mixed flow regime utilizes the momentum equation (eq. 4) and breaks it down into a dynamic component as the momentum of flow is passing through the channel cross section per unit time, and a static component as a force exerted by the hydrostatic pressure of the water (Chow, 1959). The sum of the two components is called the specific force which is used to determine which flow regime is controlling (Brunner, 2002).

Model Limitations

Simulations using DAMBRK and UNET were conducted to represent flow dynamics in a natural environment. Flow modeling accuracy can be attributed to the physical representation of the fluvial system and man-made hydraulic structures. Model geometry limitations can be related to the vertical and horizontal accuracy of LiDAR data previously discussed. High water marks and the input flow hydrograph used to calibrate DAMBRK and UNET have inherent error. The quality of forensic evidence can vary depending on flow dynamics and recovered debris at a particular high water location. The computation of volume for a given stage in the upper reservoir was based on the quality of LiDAR data and accuracy of stage sensors in determining the input flow hydrograph (reservoir-volume method) used in both models.

One dimensional unsteady flow models DAMBRK and UNET approximate flow in a one-dimensional plane at each cross section. These models may be less robust for complicated flow patterns in river reaches characteristic of complex topography and extreme turbulence.

Peak Discharge and Shear Stress Estimates

DAMBRK and UNET models were calibrated to high water marks and used to identify peak-flow characteristics along the western side of Proffit Mountain (fig. 13). UNET and Steady NETwork (SNET) models were calibrated to high water marks along the East Fork Black River (fig. 14). Simulated flood-wave arrival time from the breach to the junction with the East Fork Black River was 5.5 minutes using DAMBRK, and 6.0 minutes using UNET. The UNET model predicted the flood wave took approximately 29 minutes to reach the lower reservoir from the breach. Stage data from pressure transducers on the spillway of the lower reservoir, owned and operated by Ameren UE, indicated filling of the lower reservoir at 5:46 am (approximately 30 minutes from the time of the breach). Stage hydrographs depicting peak stage for DAMBRK and UNET fell above and below the averaged high water mark near the location of the breach and the junction with the East Fork Black River (fig. 15). Peak discharges from DAMBRK and UNET models were within 0.5 percent from one another approximately 1 mi upstream from the junction, 2 percent from one another approximately one-half mi upstream from the junction, and 5 percent from one another at the junction with the East Fork Black River (fig. 16).

Shear stress can be expressed as a tangential hydrodynamic force per unit area that is important in designing channel stability and providing a threshold for initiation of sediment transport. Described for uniform flow conditions, this hydrodynamic force is equal to the effective component of the drag force acting on the body of water, parallel to the channel bottom (Chow, 1959). As applied to wetted perimeter, shear stress can be expressed as:

$$\tau_o = \gamma RS \tag{5}$$

where

τ_o is the mean boundary shear stress, in pounds per square feet (lb/ft^2);

γ is the unit weight of water, at 62.4 pounds per cubic feet (62.4 lb/ft^3);

R is the hydraulic radius, in feet (ft); and

S is the average bottom slope, in foot per foot (ft/ft).

Broken sections of the concrete parapet surrounding the upper reservoir, boulders, and large trees were transported as a result of the embankment failure. Rock riprap with a median diameter of 1 ft is recommended to protect highway ditches from erosion by flows that exhibit a shear stress of approximately 4.8 lb/ft^2 (pounds per square feet) or less (Federal Highway Administration, 2006). The average shear stress along the western side of Proffit Mountain was approximately 40 lb/ft^2. Approximately 950 ft downstream from the breach, shear stress peaked at 232 lb/ft^2. Using permissible shear stress equations developed by the Federal Highway Administration, peak shear stress of 232 lb/ft^2 would require riprap with a median diameter of approximately 15 ft to prevent erosion (Federal Highway Administration, 2006). Upstream from the lower reservoir, the average shear stress along the East Fork Black River was approximately 4 lb/ft^2. Shear stress peaked within the Shut-Ins at 144 lb/ft^2, approximately 5,700 ft downstream from State Highway N. Channel sections just downstream from the breach, the junction of Proffit Mountain with the East Fork Black River,

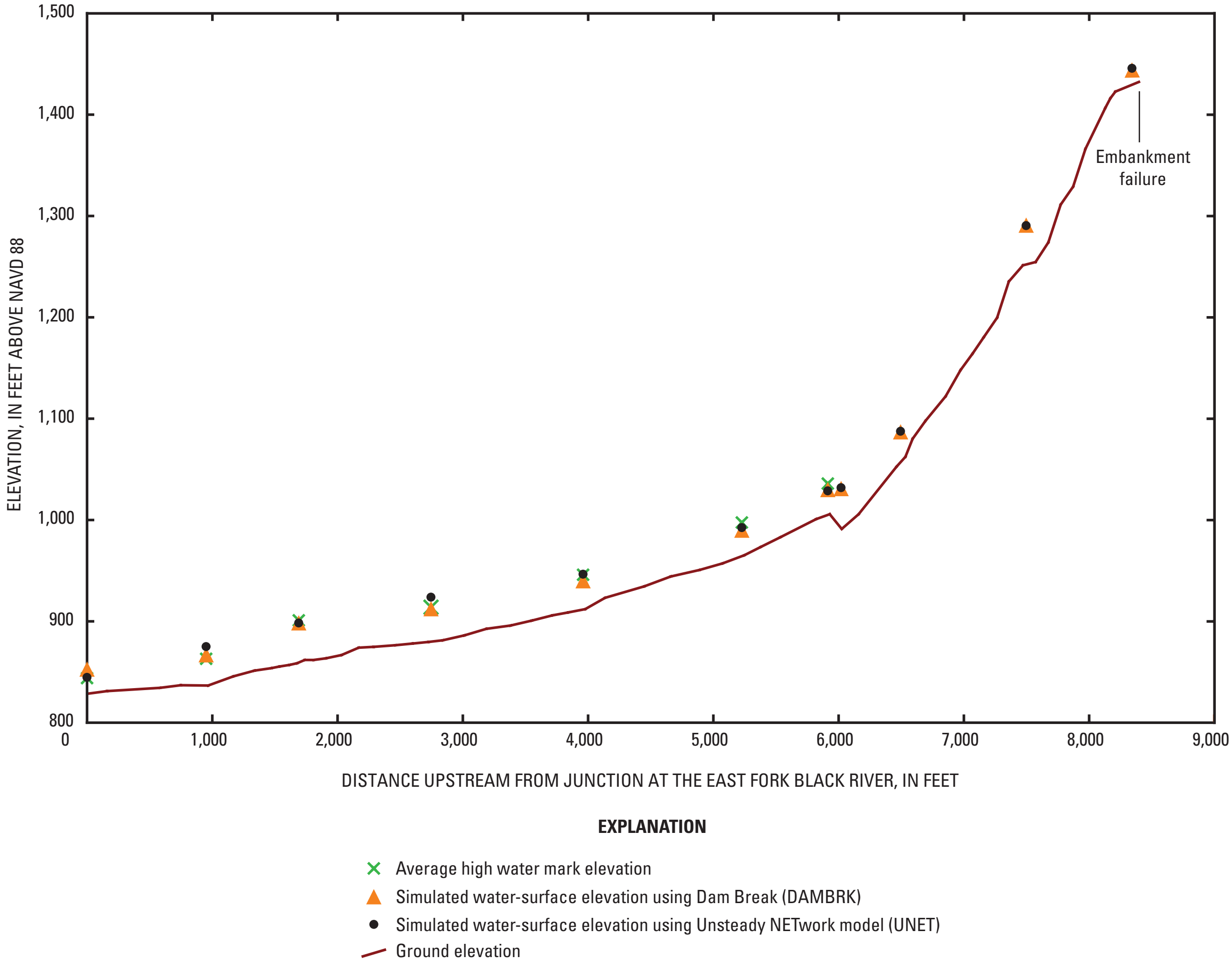


Figure 13. High water marks and simulated water-surface elevations of the embankment failure flood along the western side of Proffit Mountain using dynamic wave unsteady flow models DAMBRK and UNET.

and the Shut-Ins all exhibited substantial shear stress during the embankment failure flood (fig. 17).

Simulated velocities along Proffit Mountain ranged from 20 to 40 ft/s (foot per second) using UNET, and 21 to 51 ft/s using DAMBRK. Simulated velocities using UNET along the East Fork Black River ranged from 14 to 27 ft/s above the Shut-Ins, 31.8 ft/s at the Shut-Ins, 12 to 22 ft/s between the Shut-Ins and the bin wall, 8.5 ft/s at the bin wall, and 0.1 to 0.6 ft/s within the lower reservoir. Peak discharge, maximum water-surface elevation and velocity are shown at specific locations in tables 4 and 5.

Comparison of Embankment Failure Discharge with Natural Floods

Flood frequency estimates were compared to the embankment failure flood along the East Fork Black River to provide a contrast in magnitude as well as information vital to rehabilitation efforts within the Johnson's Shut-Ins State Park. Flood frequency determinations incorporated basin characteristics and USGS published rural regression equations by Alexander and Wilson (1995). Basin characteristics were identified using custom geographic information system (GIS) scripts that produce the overall stream length, area, and basin slope between 10 and 85 percent of the stream length. Basin area and slope (table 6) were used with Region II (Ozark Plateau physiographic region) rural regression equations for 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood events. Basin characteristics were defined at State Highway N to identify the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood magnitudes along the East Fork Black River, and upstream from the east arm of the lower reservoir at the County Road 206 crossing of Taum Sauk Creek (fig. 1) to identify 100- and 500-year flood magnitudes along Taum Sauk Creek.

A streamflow gage located approximately 2 mi upstream from County Road 206 was operational from July 1, 2001,

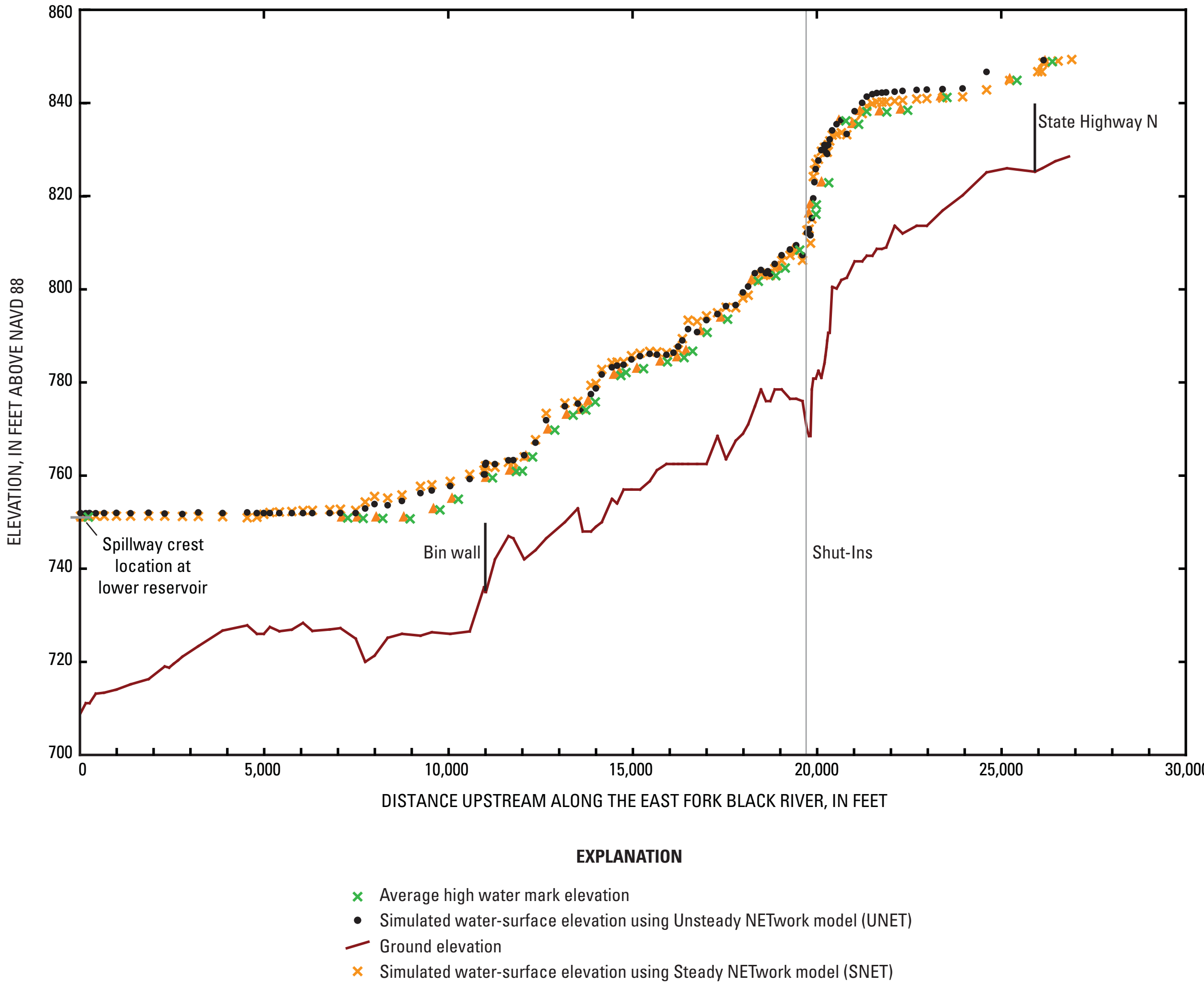


Figure 14. High water marks and simulated water-surface elevation of the embankment failure flood along the East Fork Black River using UNET and SNET.

through September 30, 2002, along Taum Sauk Creek (fig. 1) as a result of a cooperative effort between Ameren UE and USGS to identify flood magnitudes. The measured peak flow for the period of record occurred May 12, 2002, and was 8,970 ft^3/s (Hauck and Nagel, 2002).

Historic annual peak discharge was acquired from streamflow gages along the East Fork Black River at State Highway N (USGS streamflow-gaging station 07061270), just above the junction of the breach along Proffit Mountain, and at State Highway 21 (USGS streamflow-gaging station 07061300), approximately 3.7 mi downstream from the spillway of the lower reservoir. Historic annual peak discharge in water years (October 1 to September 30) is compared with flood frequency in table 7.

A comparison of the embankment failure flood to flood frequency estimates reveals 100- and 500-year flood events to be approximately 24 and 34 percent of the magnitude of the embankment failure flood, respectively. Envelope curves have been developed to provide a guide in estimating maximum flood flows for the entire United States based on thousands of observations (Crippen and Bue, 1977). Using the envelope curve for the appropriate region with the drainage area at State Highway N, the estimated maximum discharge is 63,000 ft^3/s or 66 percent of the embankment failure flood (95,000 ft^3/s) along the East Fork Black River. It should be noted that envelope curves used to estimate maximum flood flows are based on natural rainfall conditions as opposed to man-made conditions.

Embankment Failure Profiles and Natural Flood Profiles

Flood profiles were used as the foundation for developing estimated inundation extents throughout the study area. Flood

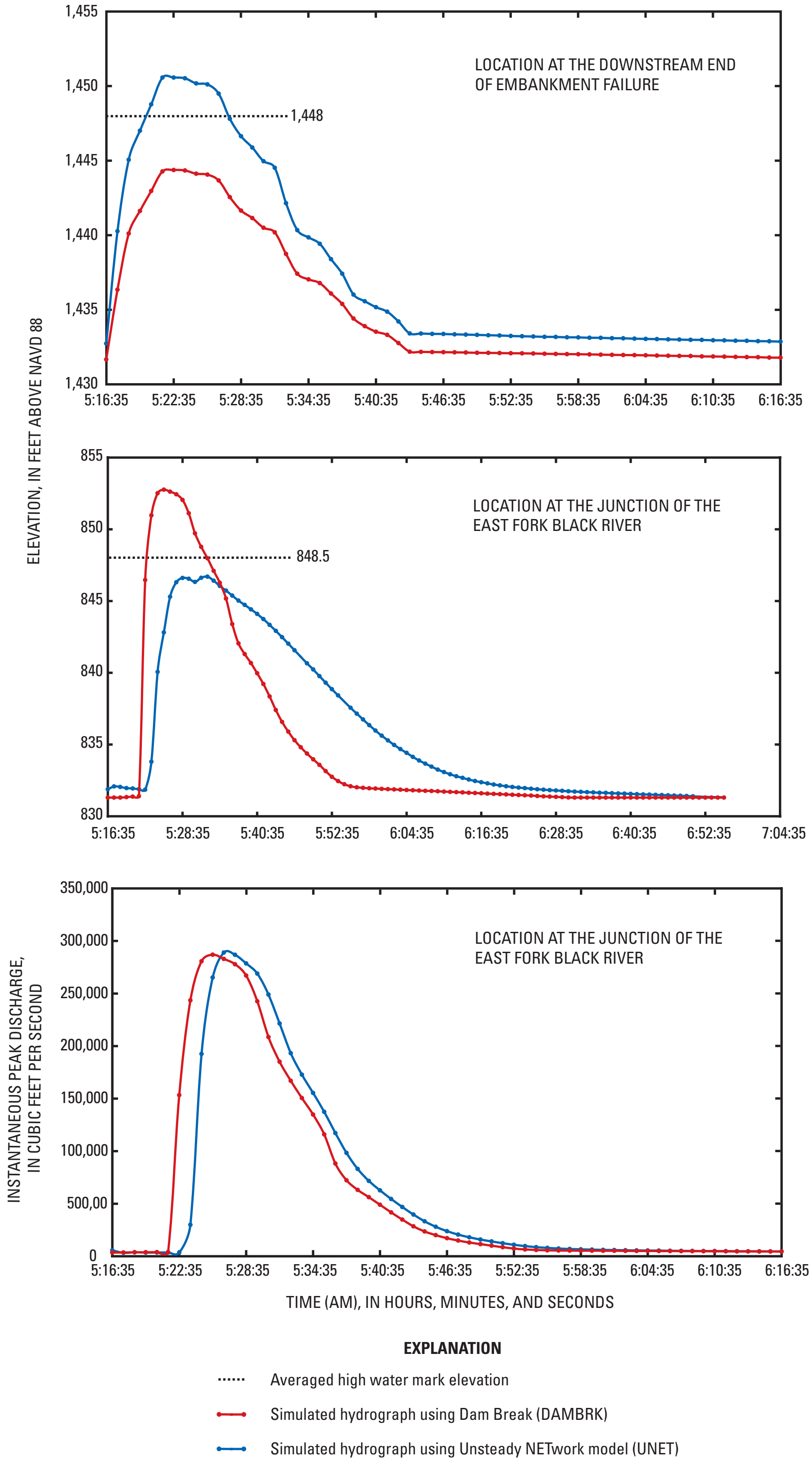


Figure 15. Stage and flow hydrographs depicting dynamic wave unsteady flow models DAMBRK and UNET along Proffit Mountain.

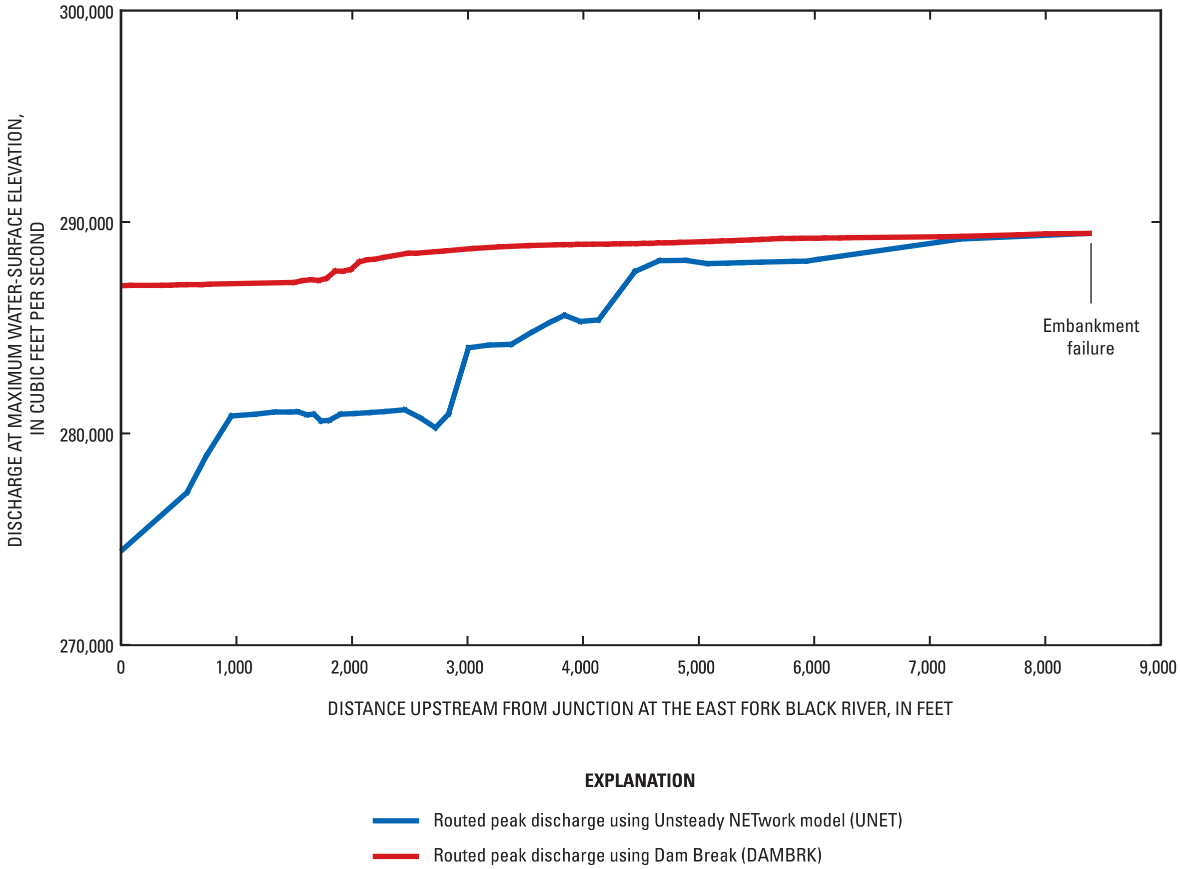


Figure 16. Peak discharge summary for the embankment failure flood along the western side of Proffit Mountain.

Table 4. Simulated flow at maximum water-surface elevation at specific locations along the western side of Proffit Mountain.

[DAMBRK; Dam Break; UNET; Unsteady NETwork model; ft, feet; ft^3/s, cubic feet per second; ft/s, feet per second]

		DAMBRK			UNET		
Location	Distance from failure (ft)	Peak discharge (ft^3/s)	Water-surface elevation (ft)	Velocity (ft/s)	Peak discharge (ft^3/s)	Water-surface elevation (ft)	Velocity (ft/s)
Downstream end of embankment failure	0	290,000	1444.5	35.8	290,000	1,450.9	34.7
Slope-area river station 23	5,150	289,000	917.9	31.8	284,000	925.5	32.5
Junction with East Fork Black River	8,170	287,000	852.8	51.3	274,000	846.6	40.0

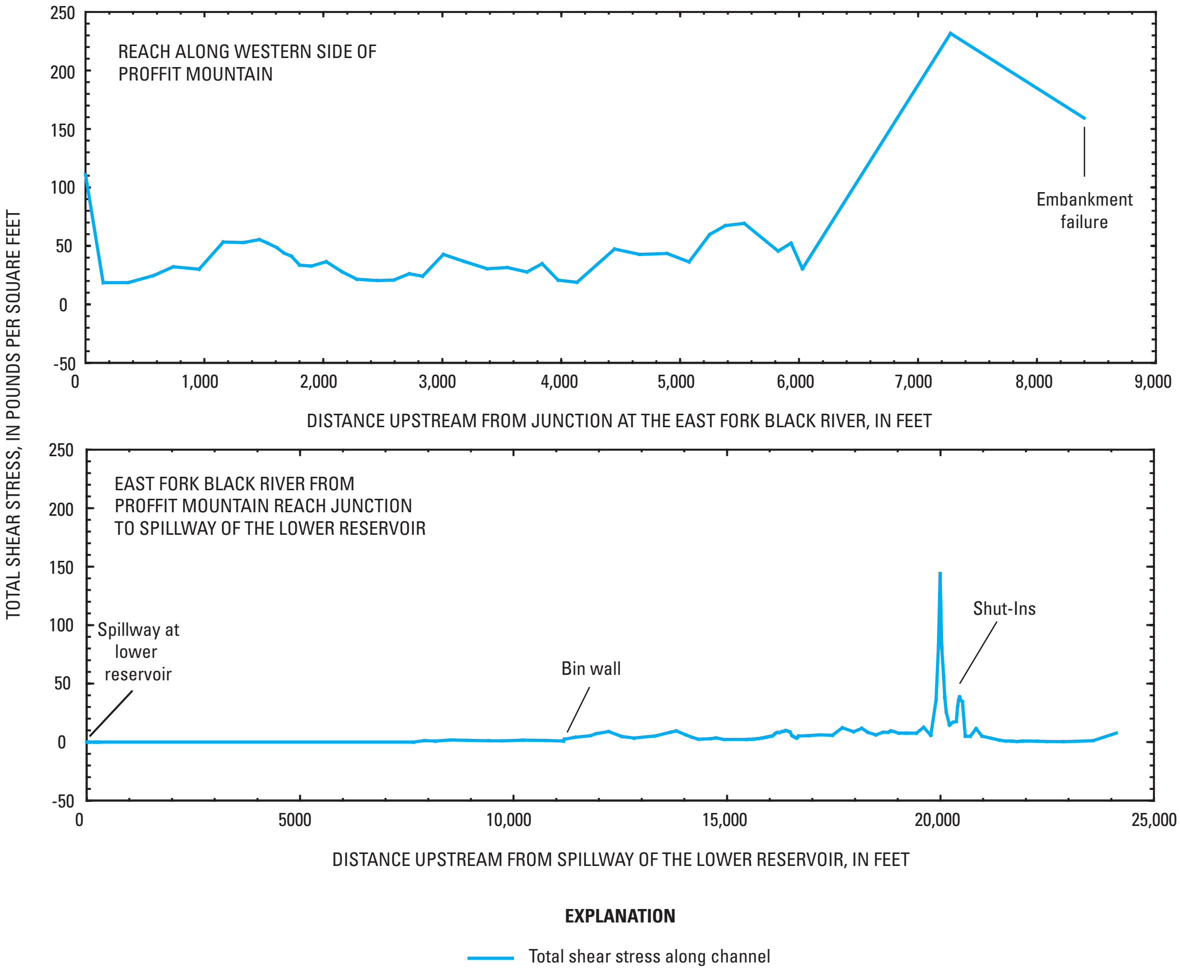


Figure 17. Total shear stress along the western side of Proffit Mountain and the East Fork Black River.

Table 5. Simulated Unsteady NETwork (UNET) flow at maximum water-surface elevation at specific locations along the East Fork Black River.

[ft, feet; ft^3/s, cubic feet per second; ft/s, feet per second]

Location	Distance from State Highway N (ft)	Peak discharge (ft^3/s)	Water-surface elevation (ft)	Velocity (ft/s)
Shut-Ins	5,700	108,000	811.6	31.8
Slope-area river station 75	6,100	107,000	809.4	20.7
Slope-area river station 54	9,430	98,000	786.0	14.8
Bin wall	14,500	96,600	762.7	8.5

Table 6. Basin area and slope defined at State Highway N and County Road 206.

[mi^2, square mile; ft/mi, foot per mile]

Location	Area (mi^2)	Slope (ft/mi)
State Highway N	52.2	38.2
County Road 206	12.9	102.9

profiles developed are the maximum stage along a reach for a given flow. Dynamic wave unsteady flow model results were used to develop embankment flood profiles from the upper reservoir to the spillway of the lower reservoir. Steady-state simulations using normal depth were used to develop flood-frequency profiles along the East Fork Black River from State Highway N, to the spillway of the lower reservoir, and along Taum Sauk Creek from the east side of the upper reservoir to the spillway of the lower reservoir. Steady-state simulations also were used to develop embankment failure flood profiles from State Highway N to the spillway of the lower reservoir and Taum Sauk Creek. All steady-state simulations were conducted using the SNET executable resident to the graphical user interface HEC-RAS.

Flood Profiles along Proffit Mountain

Embankment failure flood profiles for the Proffit Mountain reach were developed from DAMBRK and UNET model results and are presented in figure 13. Substantial wave action down Proffit Mountain was evident from high water marks (fig. 18). One-dimensional models produce a level water-surface elevation perpendicular to the direction of flow, and thus are limited in defining the oscillatory nature of the embankment failure flood profile. This limitation negates the effects of centrifugal forces producing super-elevated water surfaces. Water-surface peaks and troughs were averaged to define a water surface for one-dimensional analysis.

Flood Profiles along the East Fork Black River

Embankment failure flood profiles for the East Fork Black River were developed from UNET model results (fig. 14), and SNET model results. The SNET model developed for the embankment failure flood maintained the same channel geometry, roughness characteristics, and energy loss coefficients throughout the East Fork Black River as the UNET model. The embankment failure SNET model accounted for flow change locations above (120,000 ft^3/s) and below (90,000 ft^3/s) the junction with the Proffit Mountain reach. The east arm of the lower reservoir was modeled as a storage area and split flow was optimized to provide attenuation of peak flow and storage effects. Mixed flow regime calculations required upstream and downstream boundary conditions for supercritical and subcritical flow computations respectively. Boundary conditions were satisfied with an upstream and downstream slope of 0.033 and 0.001 ft/ft, respectively.

All headwater flood profiles representing 2-, 5-, 10-, 25-, 50-, 100- and 500-year flood frequency were characterized along the East Fork Black River from State Highway N to the spillway of the lower reservoir using SNET (fig. 19). In July 2006, a stream restoration plan was approved by several governing agencies (Mattingly and others, 2006). The objective was to restore a previously channelized reach of the East Fork Black River to a meandering condition supportive of substrate and aquatic habitat. The restoration plan begins approximately 275 ft downstream from State Highway N and continues downstream roughly 4,000 ft (fig. 20). The proposed effort will be accomplished by bio-engineering the new channel using rocks, root wads, and logs to provide stream bank stability and habitat. All profiles incorporated proposed channel geometry that was designed by MACTEC, Inc. (Mattingly and others, 2006) within the restoration plan. With the exception of the proposed restoration reach, the flood frequency SNET model maintained the same channel geometry, roughness characteristics, and energy loss coefficients throughout the remainder of the East Fork Black River as previously discussed models that were used to simulate the embankment failure flood. All flood-frequency profiles were developed using the normal operating pool elevation of 748 ft measured at the spillway as a worst-case tailwater condition. An upstream slope and downstream pool elevation were used for mixed flow regime calculations.

Flood Profiles along Taum Sauk Creek

Proffit Mountain is centered topographically between the valley of the East Fork Black River to the west and the valley of Taum Sauk Creek to the east (fig. 1). To assess a potential embankment failure to the east, a embankment failure flood profile was developed along Taum Sauk Creek. A generalized assumption was made that the attenuation of peak discharge that occurred at the base of Proffit Mountain and the East Fork Black River would be identical to the attenuation of peak discharge at the base of Proffit Mountain and Taum Sauk Creek. The resultant peak discharge of 95,000 ft^3/s that was identified from the embankment failure flood along the East Fork Black River was applied as the same peak discharge along Taum Sauk Creek. It should be noted that the floodplain configuration and geometry of Taum Sauk Creek is much different than that of the East Fork Black River at the base of Proffit Mountain. As a result, attenuation and storage effects from a embankment failure along the east wall may likely be different, resulting in a much different peak discharge along Taum Sauk Creek. In addition to developing the embankment failure flood profile, 100- and 500-year flood profiles were developed along Taum Sauk Creek (fig. 21).

Table 7. Historic peak discharge and flood magnitude and frequency along the East Fork Black River.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; --, undefined stage-discharge relation]

State Highway 21 USGS streamflow-gaging station 07061300		State Highway N USGS streamflow-gaging station 07061270		Flood magnitude and frequency at State Highway N	
Water year	**Discharge (ft^3/s)**	**Water year**	**Discharge (ft^3/s)**	**Recurrence interval *t*-year**	**Estimated discharge (ft^3/s)**
1961	7,200	2003	--	2	3,720
1962	2,920	2004	3,740	5	7,420
1963	1,810	2005	2,600	10	10,500
1964	4,480			25	15,000
1965	825			50	18,300
1966	6,450			100	21,900
1967	2,150			500	30,500
1968	7,650				
1969	5,400				
1970	5,100				
1971	2,430				
1972	8,250				
1973	10,400				
1974	6,270				
1975	6,590				
1976	2,280				
1977	9,920				
1978	2,860				
1979	8,420				
1980	1,330				
1981	4,480				
1982	4,850				
1983	8,110				
1984	3,150				
1985	8,840				
1986	35,800				
1987	2,480				
1988	6,310				
1989	3,450				
1990	5,560				

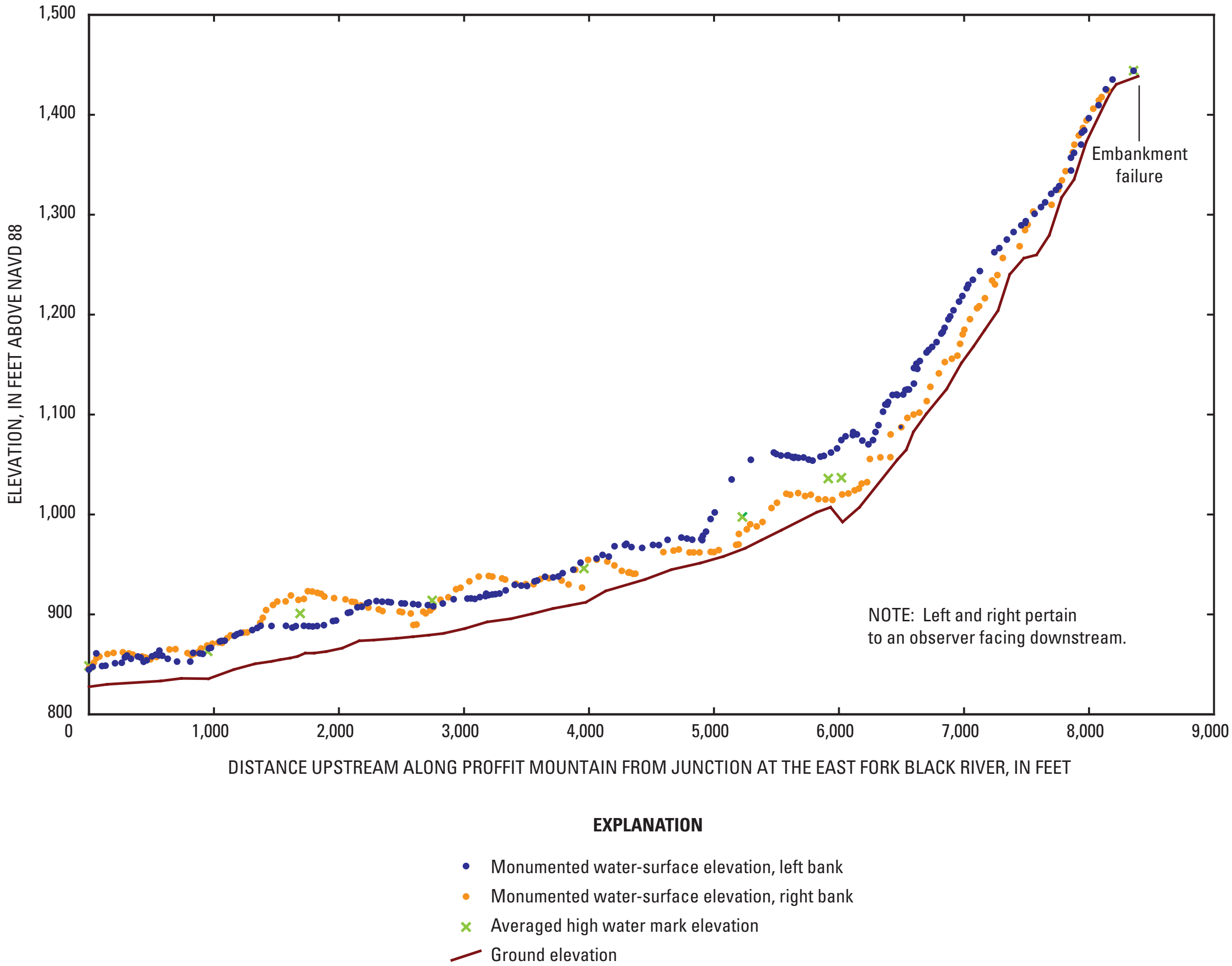


Figure 18. Left and right bank high water profiles along the western side of Proffit Mountain.

Channel geometry developed from LiDAR data and topographic surveys were used to develop the SNET model for Taum Sauk Creek (fig. 22). The west arm of the lower reservoir was modeled as a storage area and split flow was optimized to provide attenuation of peak flow and storage effects. For all discharge scenarios, the model used a normal operating pool elevation of 748 ft as a worst-case tailwater condition, and an upstream slope for mixed flow regime computations. A flow of 95,000 ft^3/s was simulated as the potential eastern embankment failure flood along Taum Sauk Creek. Flows of 11,500 ft^3/s and 16,400 ft^3/s were simulated for the 100- and 500-year floods, respectively. Channel roughness values ranged from 0.035 in the basin of the lower reservoir to 0.062 in the rugged reach at the most upstream location. Velocities ranged from 3 to 23 ft/s for the hypothetical breach of the eastern embankment failure flood from the lower reservoir to the most upstream cross section. Velocities in the lower reservoir for the hypothetical wall failure flood ranged from 0.04 to 0.14 ft/s. The measured peak discharge of 8,970 ft^3/s that occurred May 12, 2002, was between the 25- and 50-year flood event for Taum Sauk Creek (Hauck and Nagel, 2002).

Flood Inundation

Flood-inundation mapping of the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood profiles was conducted along the East Fork Black River for planning purposes and risk assessment within the Johnson's Shut-Ins State Park and nearby State Highway N. Flood-inundation mapping of the embankment failure flood profile along Proffit Mountain and the East Fork Black River was conducted to document this historic event. In addition, inundation mapping of the hypothetical east embankment failure flood, along with the 100- and 500-year flood profiles, was completed along Taum Sauk Creek.

An inundation map for the embankment failure flood was developed using GIS tools. Profiles developed from steady and unsteady flow models SNET and UNET were used to create a

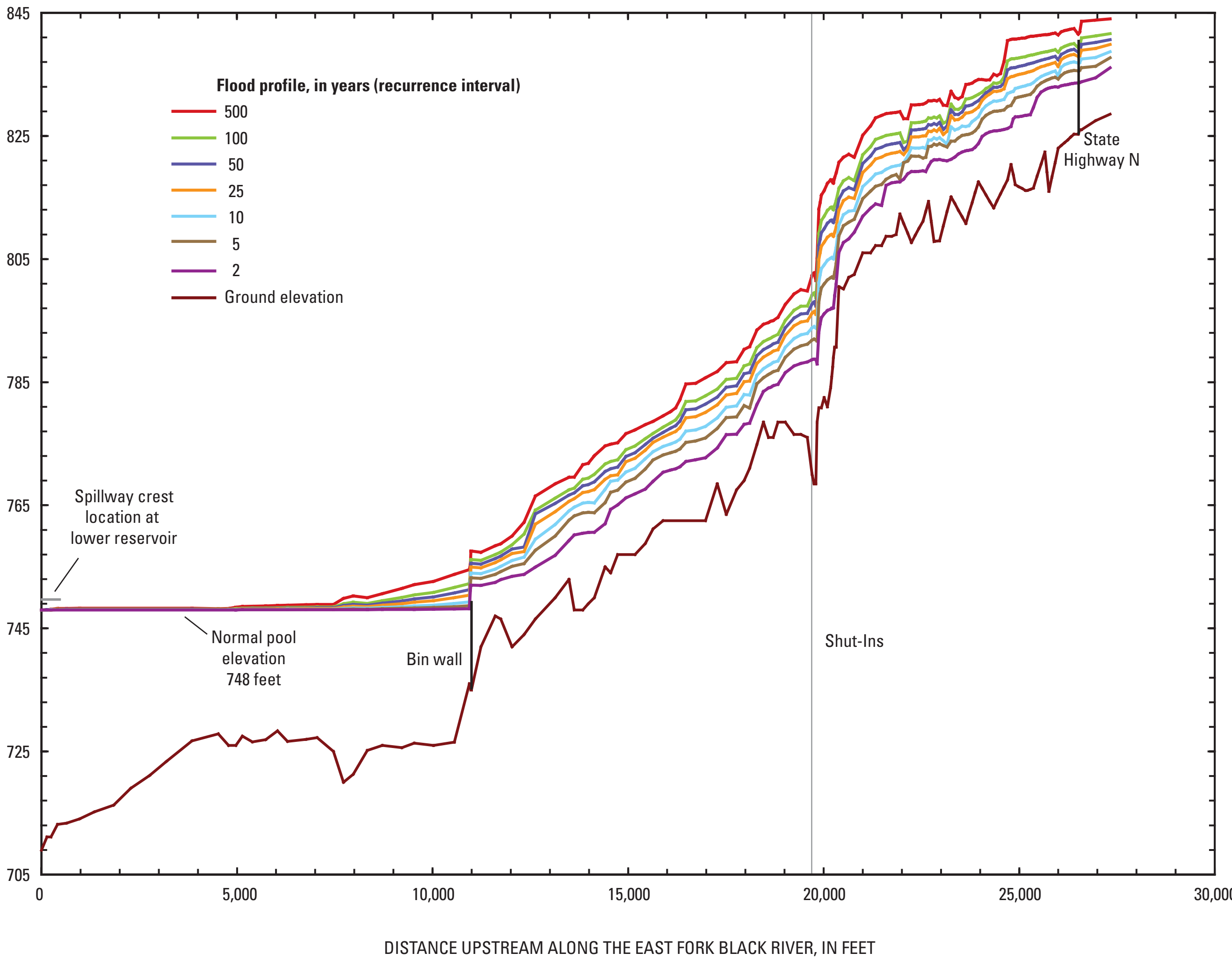
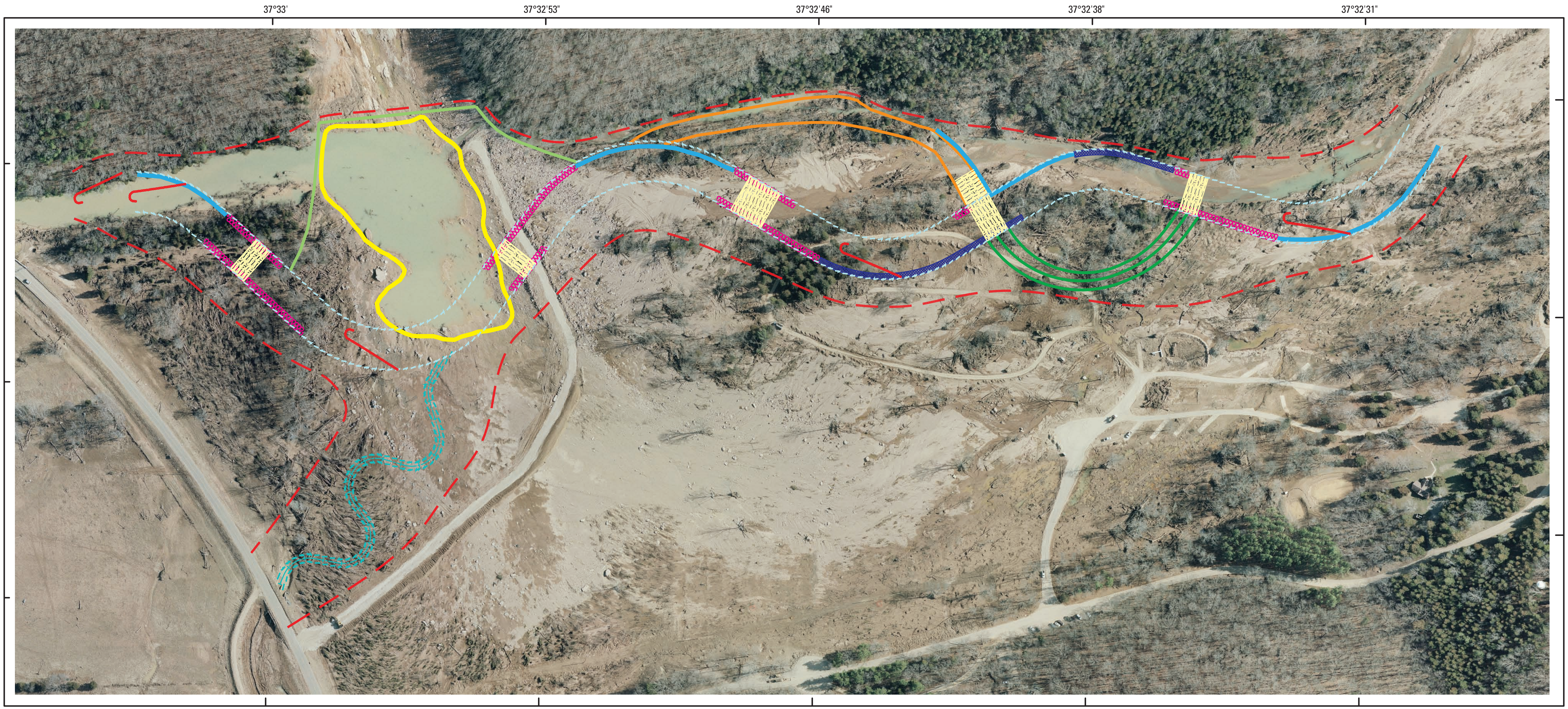


Figure 19. Simulated 2- through 500-year flood frequency profiles along the East Fork Black River from the Steady NETwork model (SNET).

water surface. The water surface was differenced from a LiDAR-generated ground surface to produce an estimated extent of inundation. The one-dimensional profile of the embankment failure flood produced lines of equal water-surface elevation perpendicular to flow. As a result, the inundation extent was further developed by making adjustments based on super-elevated surfaces from high water mark elevations shown in figure 4. An estimated flood extent of the embankment failure flood is located on the CD-ROM, at the back of this report (plate 1). High water data were used to develop an additional surface that was differenced from the LiDAR-generated ground surface to produce an extent of maximum water depth for the upper reservoir embankment failure. Average depths along Proffit Mountain and the East Fork Black River were between 10 and 30 ft. Specific locations along Proffit Mountain indicate depths may have exceeded 50 ft. Depths at the Shut-Ins ranged from 30 to 40 ft. Estimated depths along Proffit Mountain and the East Fork Black River are illustrated on plate 2, located on the CD-ROM, at the back of this report.

A similar procedure was used to create estimated inundation extents along Taum Sauk Creek. A ground surface was developed using topographic survey and LiDAR data. The ground surface was differenced with profiles representing a hypothetical east embankment failure flood and 100- and 500-year flood events. Estimated flood extents of the hypothetical east embankment failure flood, the 100-year flood, and the 500-year flood are located on the CD-ROM. at the back of this report (plates 3, 4, and 5).

Estimated inundation extents were developed for the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood profiles along the East Fork Black River from a location just above State Highway N to the spillway of the lower reservoir. The reach of channel restoration just downstream from State Highway N was incorporated as part of the process. Proposed channel design cross sections provided by MACTEC, Inc. were added to geo-referenced



Base from Surdex, Inc., proprietary to MACTEC Engineering and Consulting, Inc.
One-half foot pixel resolution, January 2006
Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the
North American Datum of 1983 (NAD 83)

Illustration and symbology from MACTEC Engineering and Consulting, Inc., 2006

EXPLANATION

Coir face with rock toe	Riparian vegetation zone	Oxbow
Cope hollow tributary	J-hook vane	Realigned channel banks
Alluvial fan extent	Wrapped earth	Riffle
Boulder fill	High-flow channel	Rootwads

0 500 1,000 FEET
0 150 300 METERS

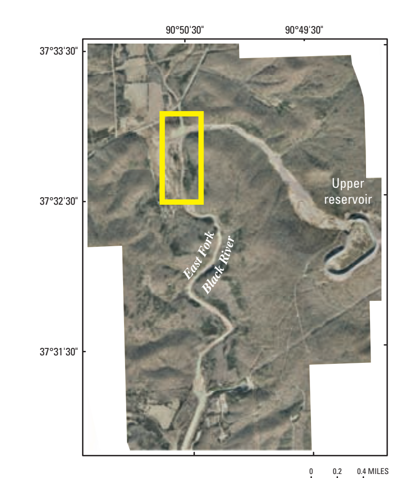


Figure 20. Proposed stream restoration plan (Mattingly and others, 2006).

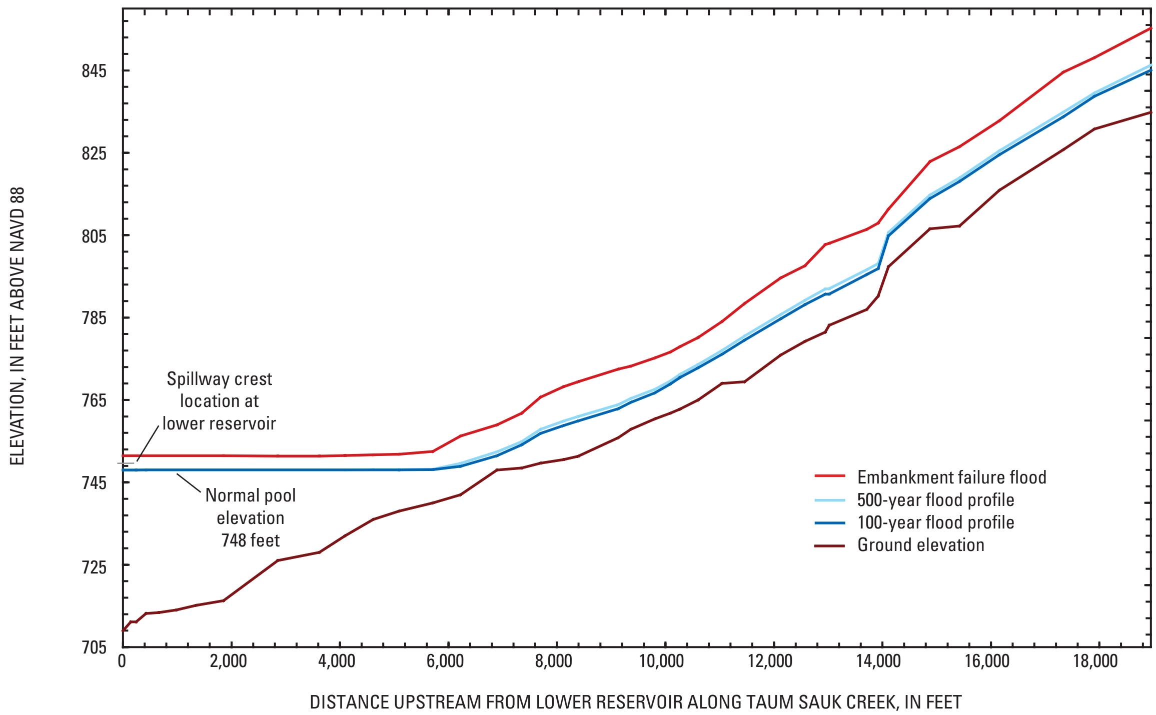


Figure 21. Simulated embankment failure flood compared with 100- and 500-year flood frequency profiles along Taum Sauk Creek from the Steady NETwork model (SNET).

0.5-ft pixel imagery (provided by MACTEC, Inc.) and plan view of proposed meandering (fig. 20). A GIS script provided interpolation of x,y,z points between each cross section along the design stream path to form a new surface for the 4,000-ft proposed reach. The new surface was blended with the existing surface to form modified ground geometry that was differenced with the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood surfaces. Estimated flood inundation extents for the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood surfaces are located on the CD-ROM, at the back of this report (plates 6, 7, 8, 9, 10, 11, and 12).

Debris Movement

The force of the embankment failure flood changed the geomorphic landscape by degrading and aggrading deposits and transporting sediment and woody debris. Texture and sedimentology of deposits along the western slope of Proffit Mountain concluded no substantial evidence to warrant a debris flow (J. Costa, U.S. Geological Survey, oral commun., 2006). A quantitative assessment was conducted to estimate the volume of sediment and debris that was transported from floodwaters entering the East Fork Black River and the lower reservoir.

Field estimates were conducted from State Highway N along the East Fork Black River to the bin wall upstream from the lower reservoir. Areas of the deposition were defined using GPS in conjunction with high-resolution color imagery. Quantitative estimates of deposition were recorded within identified areas and documented as sand/gravel and woody debris (fig. 23).

Another approach in determining debris movement was to difference the current (2006) LiDAR surface from a pre-existing 10-meter DEM based on 1:24,000 scale topography (fig. 24). Substantial differences in data density between current LiDAR point data and pre-existing elevation data used to create the DEM limited the accuracy of the resulting difference map. Using a GIS technique, an estimated 180 acres of timber were affected along the western side of Proffit Mountain to a location at the Shut-Ins. During field reconnaissance, much of the woody debris was observed being reduced to mulch to be used along foot paths within the Johnson’s Shut-Ins State Park.

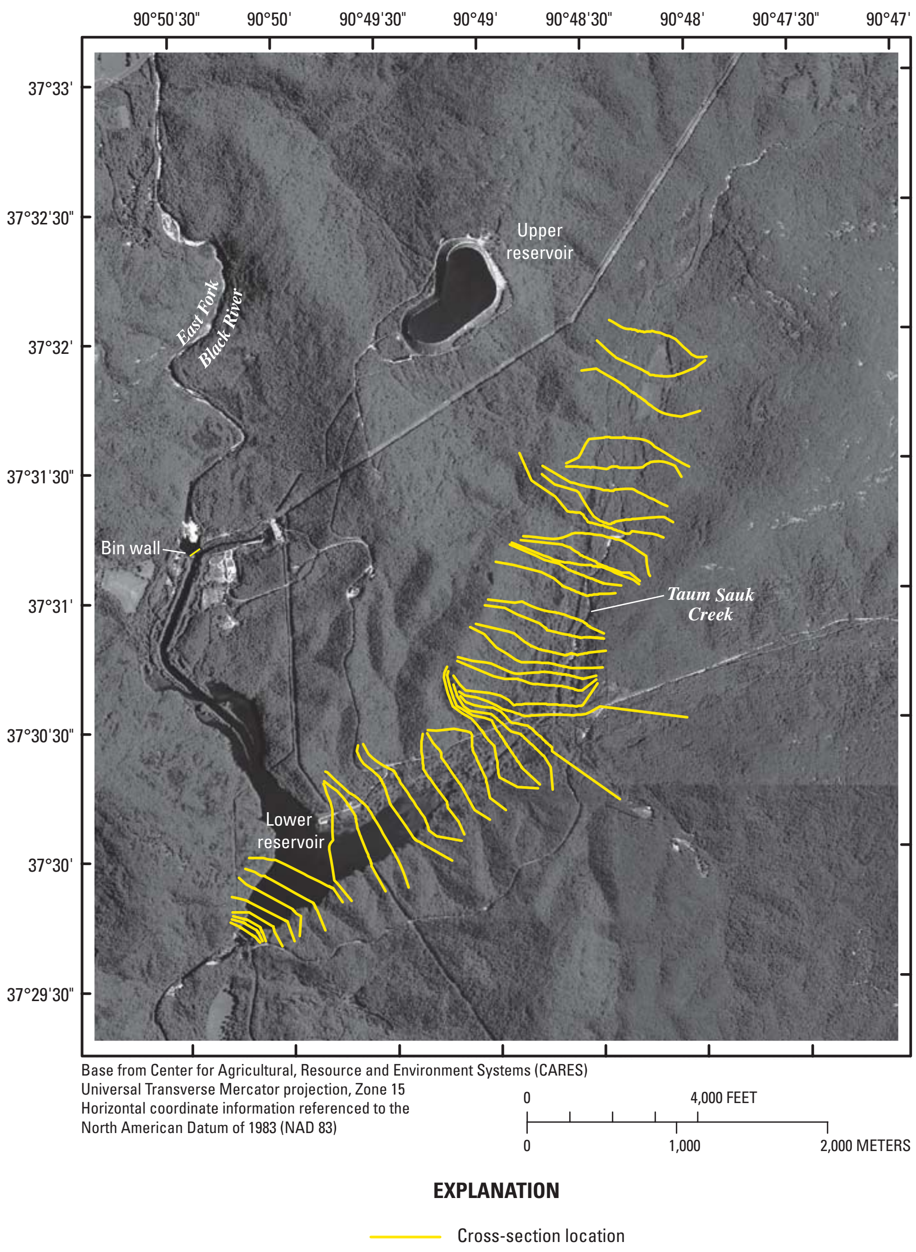
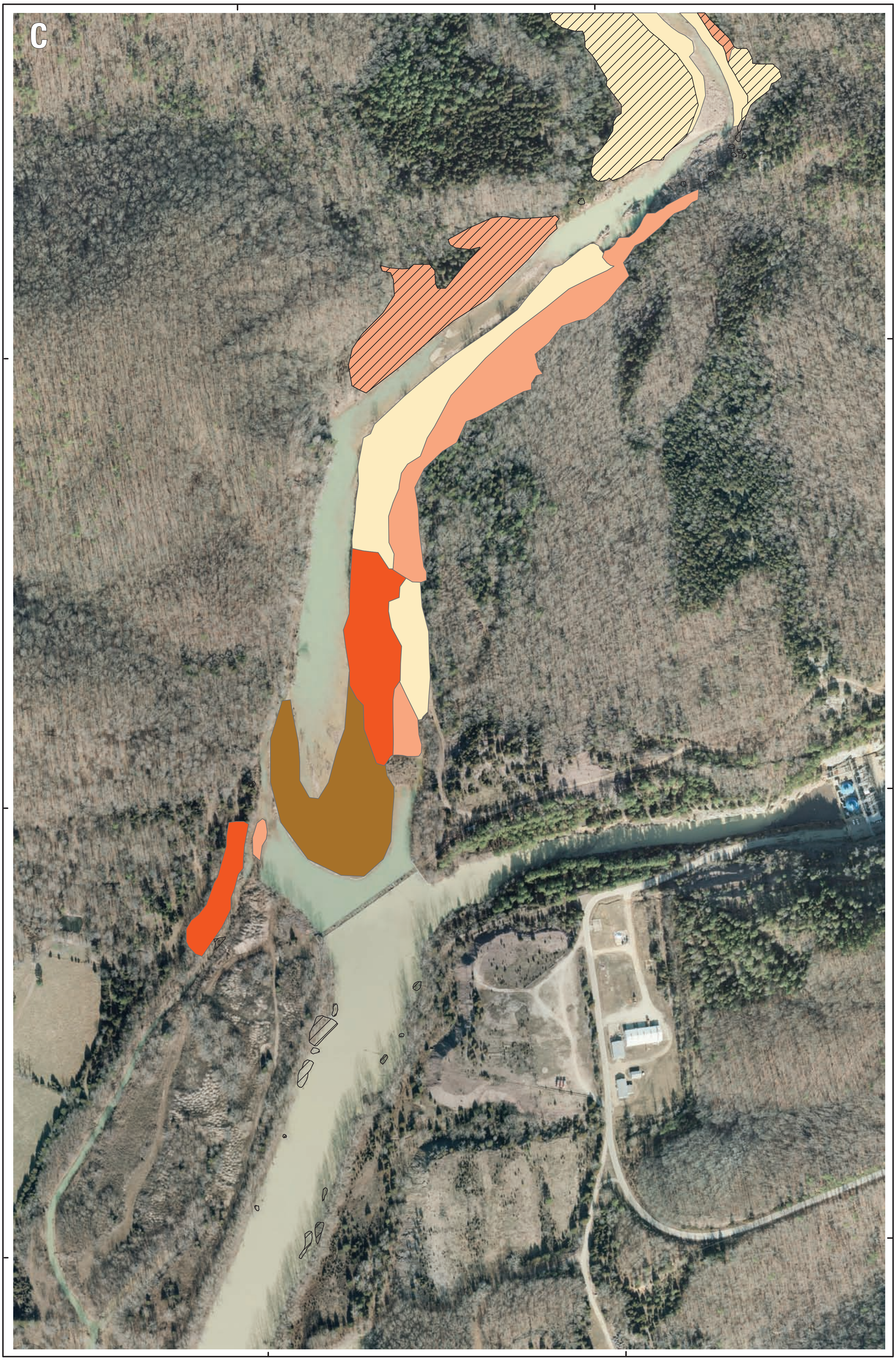


Figure 22. Location of Steady NETwork model (SNET) along Taum Sauk Creek.

Figure 23. Quantitative assessment of debris on the East Fork Black River from State Highway N to the lower reservoir near Lesterville, Missouri.

Figure 23. Quantitative assessment of debris on the East Fork Black River from State Highway N to the lower reservoir near Lesterville, Missouri.—Continued



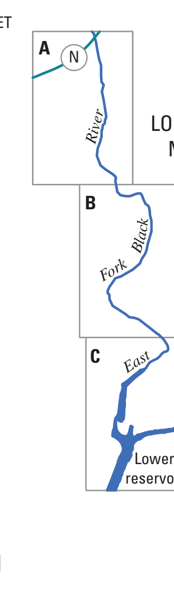
Base from Surdex, Inc., proprietary to MACTEC Engineering and Consulting, Inc.
One-half foot pixel resolution, January 2006
Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the
North American Datum of 1983 (NAD 83)

0 250 500 750 FEET
0 50 100 150 200 METERS

EXPLANATION

Approximate thickness of sand/gravel, in feet.
Number in bold indicates approximate volume of area, in cubic feet; >, greater than

>0 to 0.5 **143,000**
>0.5 to 1.0 **263,000**
>1.0 to 2.0 **249,000**
>2.0 to 3.0 **458,000**
Woody debris



LOCATION MAPS

Figure 23. Quantitative assessment of debris on the East Fork Black River from State Highway N to the lower reservoir near Lesterville, Missouri.—Continued

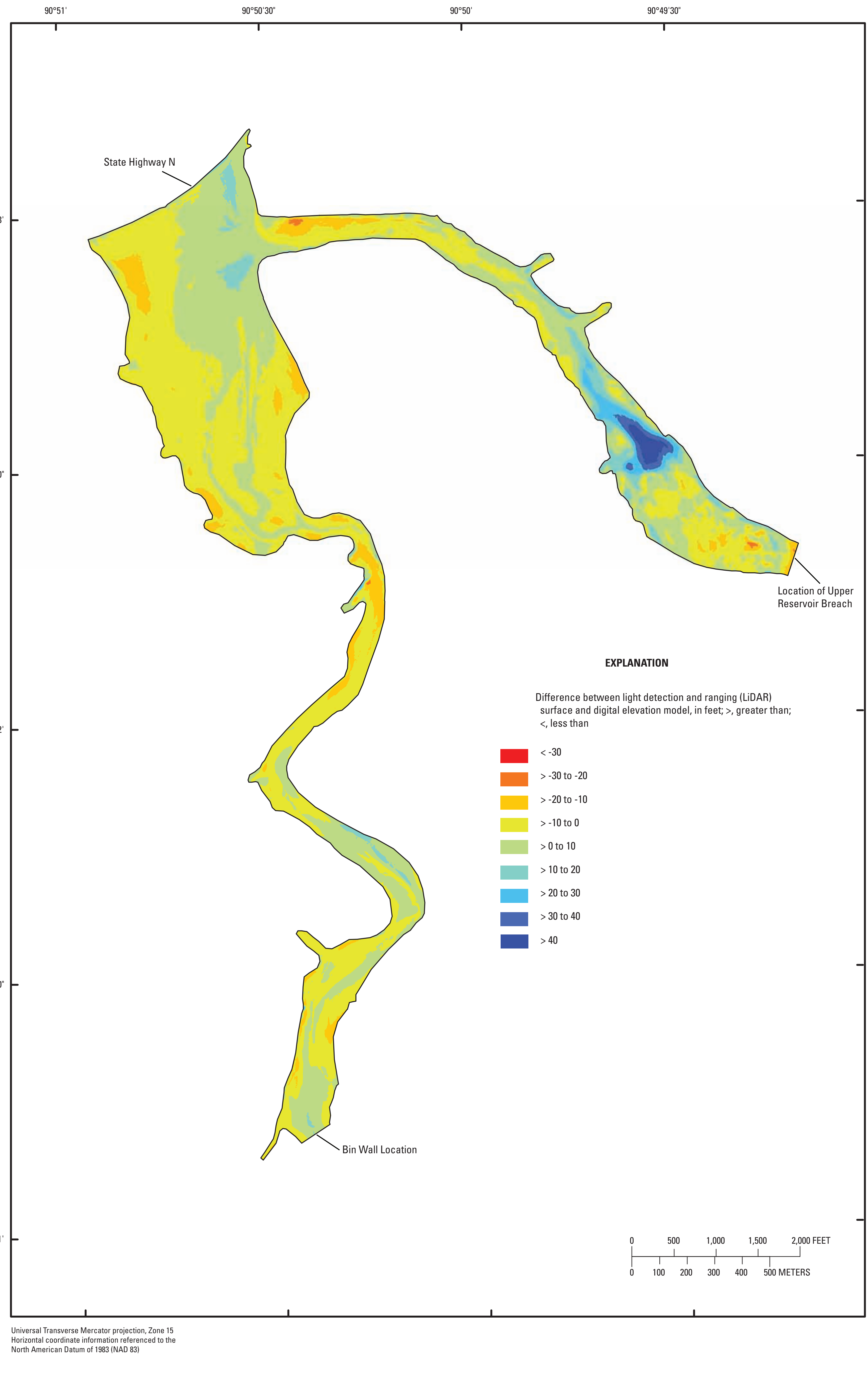


Figure 24. Difference between LiDAR surface and 10-meter digital elevation model for area upstream from the bin wall of the lower reservoir affected by embankment failure flood near Lesterville, Missouri.

Upper reservoir embankment failure flood damage at the entrance and vicinity of the Johnson’s Shut-Ins State Park (photograph courtesy of Ken Beck, Reynolds County Courier, 2005).

Summary

A pump-storage hydroelectric power plant, owned and operated by Ameren UE, is located 8 miles north of the town of Lesterville, in Reynolds County, Missouri. The plant includes an upper and lower reservoir used to provide pressure head for reversible turbines that operate as generators during peak energy use, and as pumps to fill the upper reservoir during nights and weekends when energy demand is low.

At approximately 5:16 am on December 14, 2005, a 680-foot wide section of the upper reservoir embankment failed, sending water rushing down a small steep tributary along the western side of Proffit Mountain, and emptying into the East Fork Black River that flows through the Johnson’s Shut-Ins State Park. Embankment failure floods such as this have a permanent impact on the geomorphic landscape and provide valuable information pertaining to flood hydraulics and unit peak discharge within the surrounding watershed. Such floods disrupt ecological and fluvial systems by altering channel configurations, substrate, and sediment load.

Documentation of peak discharge, flood profile, flood inundation, and debris movement from the embankment failure flood was conducted for this historic event. A survey campaign initiated on December 16, 2005, collected Light Detection and Ranging (LiDAR) derived mass points that were used to provide channel geometry for indirect measurements of peak discharge, geometry for hydraulic modeling necessary to define flood profiles, and ground surface development used to difference flood profiles and produce estimated flood extents and flood depths. Estimated flood depths may have reached greater than 50 feet along Proffit Mountain, and as much as 30 to 40 feet along the East Fork Black River.

A bathymetric survey of the lower reservoir was conducted December 22 to 23, 2005, to examine the impact of sedimentation. Approximately 318,000 data points were used to derive a bathymetric surface and resulting area/capacity table. The December 2005 bathymetric surface was differenced from a previous bathymetric survey from April 2005 to analyze areas of increasing and decreasing sediment. The greatest volume difference of 147 acre-feet occurred at an elevation of 730 feet.

Peak discharge estimates of 289,000 cubic feet per second along Proffit Mountain and 95,000 cubic feet per second along the East Fork Black River were determined through indirect measurement techniques involving volume and drawdown analysis of the upper reservoir and the slope-area method.

A dynamic wave unsteady flow routing model, Dam Break (DAMBRK), was used to route the flood wave from the breach of the upper reservoir to the junction with the East Fork Black River. An additional dynamic wave unsteady flow routing model, Unsteady NETwork (UNET), was used to route the embankment failure flood wave from the breach of the upper reservoir to the junction with the East Fork Black River and further downstream to the spillway of the lower reservoir. Both DAMBRK and UNET predicted the flood wave arrival time from the breach to the junction with the East Fork Black River, between 5.5 to 6.0 minutes. UNET predicted the flood wave would take approximately 29 minutes to reach the lower reservoir from the breach. Simulated velocities ranged from 20 to 51 feet per second along Proffit Mountain. Simulated velocities ranged from 12 to 32 feet per second along the East Fork Black River between the junction with the Proffit Mountain reach and the bin wall just above the lower reservoir. Velocities ranged from 0.1 to 0.6 feet per second in the lower reservoir. The highest velocities were identified at the junction of the East Fork Black River with the Proffit Mountain reach. Along the western side of Proffit Mountain, shear stress reached a peak of 232 pounds per square foot, approximately 950 feet downstream from the breach. Along the East Fork Black River shear stress peaked within the Shut-Ins at 144 pounds per square foot, approximately 5,700 feet downstream from State Highway N.

Flood profiles and inundation extents representing 2-, 5-, 10-, 25-, 50-, 100-, and 500-year flood frequency incorporated a proposed reach of channel restoration, and were developed from State Highway N to the spillway of the lower reservoir.

Flood profiles and inundation extents were developed along Taum Sauk Creek for a hypothetical breach of the eastern embankment of the upper reservoir, as well as 100- and 500-year flood frequency. Velocities ranged from 3 to 23 feet per second for the hypothetical breach of the eastern embankment failure flood from the lower reservoir to the most upstream cross section. Velocities in the lower reservoir ranged from 0.04 to 0.14 feet per second for the hypothetical breach.

The embankment failure flood provided enough shear stress to initiate the movement of sediment and woody debris. A quantitative assessment of debris movement was conducted to provide volume estimates beneficial toward re-habilitation efforts within the Johnson's Shut-Ins State Park. High resolution imagery acquired by MACTEC, Inc., was combined with field estimates to identify areas of deposition and respective volume. Debris movement was categorized as sand/gravel or woody debris.

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